MEDICAL PHYSICS
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EDITORIAL
MICHEL TER-POGOSSIAN AND THE DEVELOPMENT OF POSITRON EMISSION TOMOGRAPHY (PET)
THE RISE AND FALL OF THE RECTILINEAR SCANNER IN NUCLEAR MEDICINE
HISTORY OF PIONEER WOMEN IN MEDICAL PHYSICS
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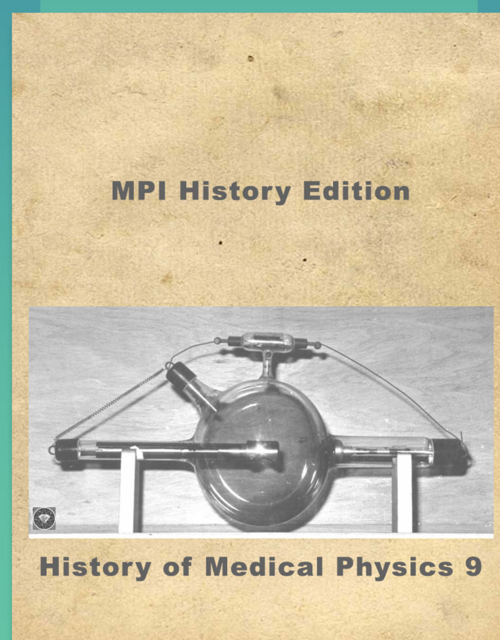
A BRIEF HISTORY OF POSITRON EMISSION TOMOGRAPHY



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EDITORIAL

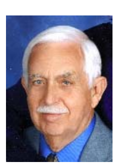
Slavik Tabakov, Perry Sprawls and Geoffrey Ibbott
Co-Editors of MPI History Editions (previously known as MPI Special Issues)

Most of the modern medical imaging and radiation therapy methods we use today are the results of many years of research and development and collaborative efforts of physicists, often along with engineers, physicians, and other scientists. Often, the vision and dedicated investigations into new areas establish these researchers as our Medical Physics Pioneers. This 9th issue of the *Medical Physics International History Edition* (MPI-HE), previously known as *MPI Special Issues* dedicated to history, marks the surpassing of 1000 pages of published materials about the history of medical physics. Starting in 2018 MPI-HE attracts thousands of readers per month at http://www.mpijournal.org/history.aspx . The articles published in this Journal have two major objectives. One is insight into the innovations and continuing developments of our medical technologies and applications plus the overall global development of medical physics. The other is getting to know our pioneers, not only their achievements and contributions, but also perhaps seeing them as role models and examples of what physicists can provide to advance the science and practice of medicine. The current MPI-HE issue No.9 includes papers related to the History of Positron Emission Tomography, Rectilinear Scanners, and Brachytherapy. Additionally, it includes papers related to the achievements of women in medical physics – both pioneers and current contributors (for this we collaborated with the IOMP WSC Chair Prof. L Marcu) and the IDMP establishment.

The History topics extensively covered in MPI-HE so far include:
MPI-HE 1- http://www.mpijournal.org/pdf/2018-SI-01/MPI-2018-SI-01.pdf with papers on history of:
*X-ray Tubes; *Film-Screen Receptors; *Medical Physics e-Learning Introduction
MPI-HE 2 - http://www.mpijournal.org/pdf/2019-SI-02/MPI-2019-SI-02.pdf with papers on history of:
*Fluoroscopy; *Mammography; *Review of the Physics of Mammography
MPI-HE 3 - http://www.mpijournal.org/pdf/2020-SI-03/MPI-2020-SI-03.pdf with papers on history of:
*Dental Radiography ; *Contrast Media X-Ray Diagnostic Radiology; *Medical Physics in Africa
MPI-HE 4 - http://www.mpijournal.org/pdf/2020-SI-04/MPI-2020-SI-04.pdf with papers on history of:
*Cobalt-60 Radiation Therapy; *Computed Tomography; *Medical Physics in South-East Asia and in Eastern Europe
MPI-HE 5 - http://www.mpijournal.org/pdf/2021-SI-05/MPI-2021-SI-05.pdf with papers on history of:
* Ultrasound;* Acoustic Pressure Measurement;* Acoustic Power Measurement; *Thermal Ultrasound Measurement
MPI-HE 6 - http://www.mpijournal.org/pdf/2021-SI-06/MPI-2021-SI-06.pdf with papers on history of:
*Medical Ultrasound-Imaging; *Diasonograph; *HP Ultrasound Imaging; *Doppler Ultrasound; *HIFU Therapy
MPI-HE 7 - http://www.mpijournal.org/pdf/2022-SI-07/MPI-2022-SI-07.pdf with papers on history of:
*History of IOMP; *IOMP History tables with the names of all IOMP contributors in its 60 year history.
MPI-HE 8 - http://www.mpijournal.org/pdf/2022-SI-08/MPI-2022-SI-08.pdf with papers on history of:
*Medical Physics teaching; External-Beam Radiotherapy Fractionation; Medical Physics teaching in medicine, etc.

Additionally, history information about the development of medical physics in all continents can be seen in the Regular issues of MPI 2019-2021, where all IOMP Regional Organisations included papers about the professional and educational development in many of the countries within their geographical areas. The content of the MPI-HE (previously known as Special History Issues) of the Medical Physics International (MPI) Journal supports the objective of the History project: to research, organize, preserve, and publish on the evolution and developments of medical physics and clinical applications that are the foundations of our profession. Our young medical physicists and students will benefit from getting to know our pioneers. This can be achieved by sharing these articles and including presentations and discussions within your education and training programs. We are grateful to all authors who submitted papers and to the Technical Editor M Stoeva. We welcome contributions of colleagues from all societies, organizations and companies who would like to join the History project with articles on specific topics. We look forward to receiving your suggestions.


Prof. Slavik Tabakov


Prof. Perry Sprawls


Prof. Geoffrey Ibbott

MICHEL TER-POGOSSIAN AND THE DEVELOPMENT OF POSITRON EMISSION TOMOGRAPHY (PET)

L. Rothenberg [1], P. Sprawls[2]

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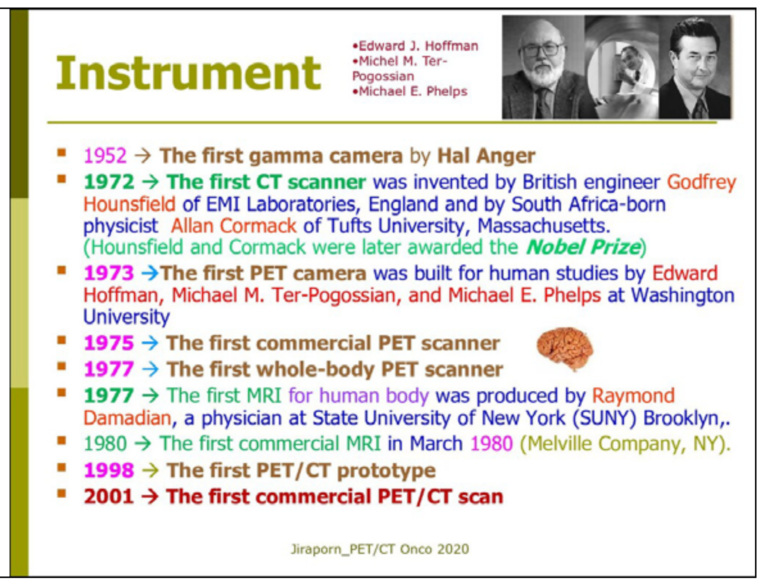
[2] Emory University, Atlanta, and Sprawls Educational Foundation, www.sprawls.org

I. INTRODUCTION

Although the development of most medical imaging methods and technologies is the result of contributions by a team of physicists, engineers, and physicians, there is often one individual whose vision, research, and leadership are a major factor resulting in the innovations and new imaging modalities. Physicist Michel Ter-Pogossian is one of those. Included in his extensive career was the recognition of the value and promotion of short-life radionuclides, especially oxygen-15, a positron emitter, for both research and clinical diagnostic procedures. This required the development and installation of cyclotrons within the clinic and methods for measuring radioactive uptake and decay in specific organs. Imaging the radiation from positron-emitting radionuclides with technology available at that time was a challenge because the high energy (511 keV) annihilation radiation was beyond the effective range of collimators. This ultimately led to imaging methods using time-of flight and co-instance localization and the development of positron emission tomography (PET. This resulted from the efforts of many medical imaging professionals, but for his major contributions Dr. Ter-Pogossian has been recognized as a "Father of PET".

Positron Emission Tomography (PET) is one of several computerized tomography imaging methods that are the foundations of modern clinical methods that have developed over the years.



PET is related to the other imaging modalities in several ways. The most significant was it provided visualization of conditions and functions within the human body not possible with the other methods. Although radionuclide imaging was well established with the gamma camera, including single-photon emission tomography (SPECT), the gamma camera using physical collimation to form images was not capable of effective imaging the higher-energy, 511 keV, annihilation photons produced by positrons. PET was developed using the reconstruction method first developed by Hounsfield and Cormack for CT. A major value of PET was being combined with CT to add biological function to the high-detail CT images.

II. THE MANY ACHEIVMENTS AND CONTRIBUTIONS OF MICHEL TER-POGOSSIAN

Michel Ter-Pogossian was a pioneering medical physicist with many contributions throughout his career that are described in many publications, Reference (1, 2, 3,4). This article provides an overview of his life and career and his activities contributing to the development of positron emission tomography (PET).

Early Life

Michel Ter-Pogossian was born in Berlin, Germany on April 21, 1925, when his parents were in Germany due to an assignment that his father, a lawyer, was working as an envoy. Earlier his parents, who were Armeninan, had fled their homeland where there was ethnic persecution after World War I. Because of his family background he is frequently included in lists of famous Armenians or Famous Armenian Inventors.

When he was two months old, his family moved to Paris where Michel grew up and had his primary education. His fascination with science began as a child and was fueled by experiments involving his toy physics and chemistry kits. He attended the University of Paris and earned degrees in science from the University and from the Institute of Radium in 1943 and 1946, respectively. At the Institute of Radium, he studied under Irene Joliot-Curie. While a student he had a minor role in the French resistance and served as an advance scout when the French military was on the way back to Paris following the German retreat. He was in Paris when Charles DeGaulle arrived with the returning victorious Allied troops.

Graduate Studies In the U.S.

Ter-Pogossian moved to the United States to study at Washington University of St. Louis, where A. H. Compton, a physicist and Nobel laureate and a friend of his family, was the Chancellor of the university. There he received the M.S. degree in 1948 and a Ph.D. in Nuclear Physics in 1950.

Academic Ranks

Ter-Pogossian joined the Mallinckrodt Institute of Radiology at Washington University as an Instructor in Radiation Physics in 1950, and later held titles there of Professor of Radiation Physics in 1961, Professor of Biophysics in Physiology in 1964, and Professor of Radiation Sciences in 1973.

Research Activities in St. Louis

The physics department at Washington University had a cyclotron that had been used for atomic and nuclear research during World War II that was later converted to produce medically relevant isotopes such as 131-I and 32-P. There were efforts to produce the biologically relevant short-lived isotopes such as 11-C, 13-N, and 15-O, 18-F and a few patients were brought to that cyclotron and housed in a trailer next to the physics department for some early studies, but this probed to be an unacceptable situation. Also, the older cyclotron was designed to accelerate only deuterons. Ter-Pogossian was advised to approach the National Institutes of Health to obtain funding for a new cyclotron that would be located in the hospital complex at Washington University. He was successful in getting funding and a new cyclotron manufactured by Allis-Chalmers was obtained. With the use of the short-lived isotopes, He and his collaborators pioneered the use of radiotracers and developed practical clinical applications of cerebral scanning. His work resulted in improvements in medical imaging, external beam radiotherapy, and brachytherapy. Details of the research of Ter-Pogossian and his colleagues are given below.

Ter-Pogossian is often called the "Father of Positron Emission Tomography (PET)", although he sometimes preferred the title "Mother" since he worked with so many others to develop the early PET devices. Among those he cited as important contributors were his many colleagues at Washington University including Michael E. Phelps and Edward Hoffman, the invention of SPECT by David Kuhl and co-workers at the University of Pennsylvania, Gordon Brownell at Massachusetts General Hospital who developed the method to detect annihilation radiation from positrons, those at the Lawrence Berkely Lab who were able to produce the first medically useful radionuclides including 131I, 201Th, 99mTc, 14C, and 67Ga, James Robertson and colleagues at Brookhaven National Laboratory who built "headshirinker", a direct forerunner of PET, and Godfrey Hounsfield and Alan Cormack who developed the reconstruction algorithms which were used for PET, as well as for computed tomography.

Important Interactions in England

While working at Washington University, in the early days primarily as a radiation therapy physicist, Ter-Pogossian was able to take a six-month sabbatical where he studied with the noted physicist L.H. Gray on important animal experiments with short lived isotopes and he also visited Hammersmith Hospital in London which was operating a medical cyclotron.

Publications and Editorial Boards

Ter-Pogossian was a prolific author, with more than 250 papers and book chapters, and was a charter member of the American Nuclear Society and a fellow of the American Physical Society. He served on the editorial boards of major scientific journals, including the American Journal of Roentgenology, the Journal of Nuclear Medicine and the Journal de Biophysique & Medicine Nuclear. He also served as an adviser for several Department of Energy and National Institutes of Health committees.

Popular Diagnostic Physics Textbook

Michel Ter-Pogossian is well known to a certain generation of medical physicists for having published his outstanding textbook The Physical Aspects of Diagnostic Radiology, Hoeber Medical Division, Harper & Roe, Publishers, New York, Evanston and London, 1967. Surprisingly, there is no mention of nuclear medicine or radioactivity topics in the book. This book can be read and downloaded from the AAPM Author Archives at: DiagnosticRadiology.pdf (aapm.org)

Personal Life and Family

Michel Ter-Pogossian married Ann Scott (July 13, 1932 – April 17, 2022), who was the daughter of a major radiologist at Washington University, Dr. Wendell(?) 'Scottie" Scott. Ann was a widow with three children that Michel helped to bring up. She was an internationally known oil painter who exhibited her work initially as Ann Scott, but later as Ann Ter-Pogossian after they were married.

Michel Ter-Pogossian assumed emeritus status at Washington University in 1995. The following year while visiting Paris he died suddenly of a heart attack on June 19.

Major Awards

Michel Ter-Pogossian was honored by many organizations for his scientific endeavors including:

Paul E. Aebersold Award of the Society of Nuclear Medicine (now SNMMI) in 1976

Georg Charles de Hevesy Nuclear Medicine Pioneer Award of SNMMI 1985

Ter-Pogossian was elected the U.S. Institute of Medicine in 1987

Canada Gairdner International Award in 1993 (For Contributions to the development and application of Positron Emission Tomography)

Gold Medial Award of the Societe Francaise de Medecine Nucleare et de Biophysique

Video Interview

For those of you who would like to hear Michel Ter-Pogossian give a first-person description of his life and career, please visit the History and Heritage/Interviews section of the American Association of Physicists in Medicine website (aapm.org) to view a video interview lasting almost two hours conducted by Robert Gorson on May 24, 1993 at Washington University Medical Center in St. Louis. The link is: AAPM History and Heritage - Interviews

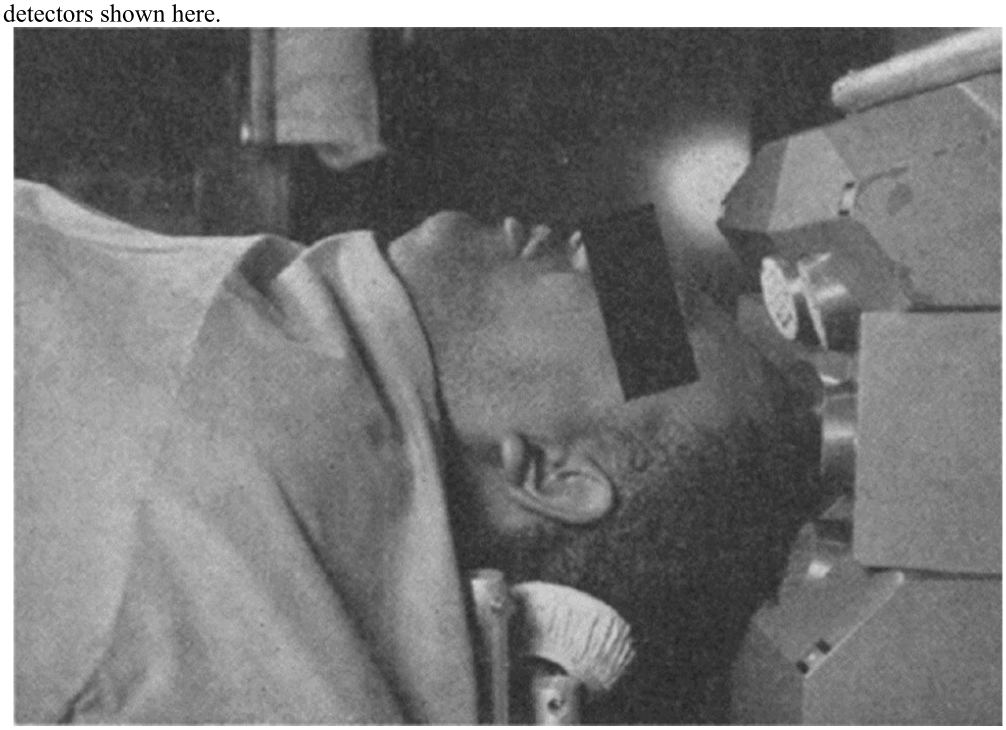
III. THE DEVELOPMENT AND EVOLUTON OF POSITRON EMISSION TOMOGRAPHY (PET)

The development of positron emission tomography (PET), as described by Ter-Pogossian, took place through the combination of the following recognitions: (1) a handful of short-lived, positron-emitting radionuclides, carbon-11, nitrogen-13, and oxygen-15, exhibit chemical properties that render them particularly suitable for the tracing of important physiological pathways, and (2) the radiation emitted as a result of the annihilation of positrons in matter exhibited physical properties that made it well-suited for nuclear medicine imaging, particularly for tomographic reconstruction. The scientific building blocks that were necessary for the structure of PET were contributed over a period of several decades by many investigators in physics, mathematics, chemistry, and fundamental biology.

A comprehensive description of the development of positron emission tomography is provided by Ter-Pogossian in his article, *The Origins of Positron Emission Tomography*, and *A brief History of Positron Tomography* by Dayton A. Rich. These are included in the APPENDIX of this article where they can be read in detail. Much of the following is based on and contains excerpts from these articles article along with references to other publications by Ter-Pogossian.

IV. THE VALUE OF SHORT LIFE RADIONUCLIDES

Generally, nuclear medicine imaging was limited to the use of radionuclides with relatively long half-lives because of technical limitations of producing, administering, and imaging before the nuclide decayed below a measurable level. Also, the lifetime of the radionuclide needed to be sufficiently long in relationship to dynamic physiology functions to provide for their measurement. For example, ^{15}O was thought to be clinically useless because of a short half-life (122.5 s) making it biologically insignificant. However, Ter-Pogossian in collaboration with others, used and demonstrated its value in several physiological studies, Reference (5) . ^{15}O was used as ^{15}O–O^{2}, ^{15}O–CO, and ^{15}O–CO^{2}, for respiratory.
and cerebral metabolic studies. diseases. In a study, a small volume of blood with radioactive ^{15}O labeled hemoglobin (^{15}O-Hb) was rapidly injected into the
internal carotid artery of a patient. The buildup and decay of activity in the brain was measured with a configuration of six scintillation detectors shown here.

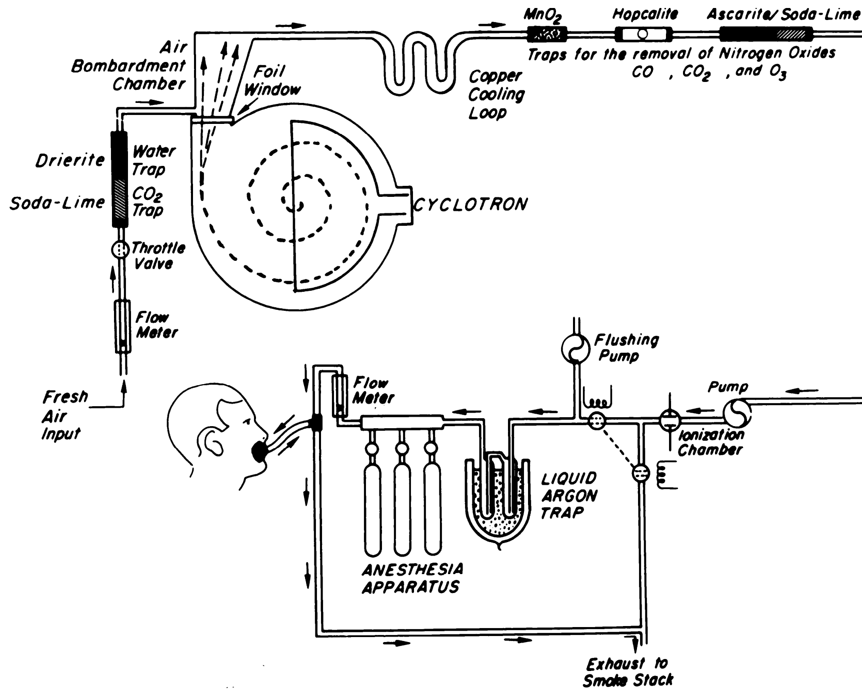


His analysis of the data provided a measurement of fractional oxygen utilization in the brain and regional cerebral oxygen utilization rates, Reference (6).

V. *CYCLOTRONS TO PRODUCE SHORT LIFE RADIONUCLIDES IN THE CLINIC*

The positron-emitting radionuclides, carbon-11, nitrogen-13, and oxygen-15 are produced with proton bombardment in cyclotrons. At that time, cyclotrons were well developed and used in many institutions and organizations around the world. What was needed to produce the medically useful position emitting radionuclides were relatively small cyclotrons located in the clinic, not other departments some distance away. MT visited several cyclotron producers and installations, including in Japan and England, to learn more about their characteristics and capabilities.

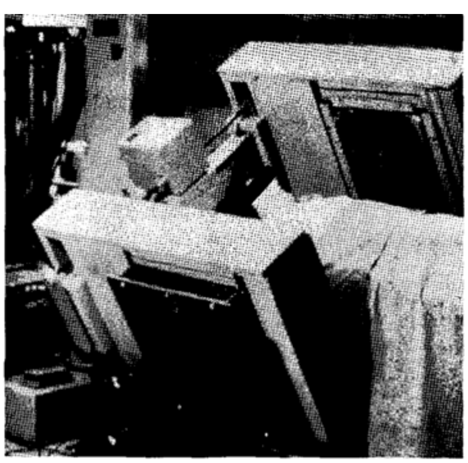
The decision was to install a cyclotron at the Washington University Medical Center manufactured by the Allis-Chalmers Company but by specifications developed by Ter-Pogossian and colleagues. This diagram shows the system used to deliver purified radioactive oxygen to a patient to evaluate respiratory function.



A full description of the characteristics and use of cyclotrons for producing radionuclides for imaging is described by Ter-Pogossian in Reference (7).

VI. IMAGING SHORT LIFE RADIONUCLIDES

Initially, gamma cameras were used to image radiation from the short-life radionuclides in clinical procedures, including tomographic imaging. That was the technology available at the time. However, it was limited because the collimators were not efficient for the 511 keV photon annihilation radiation emitted by the positrons.



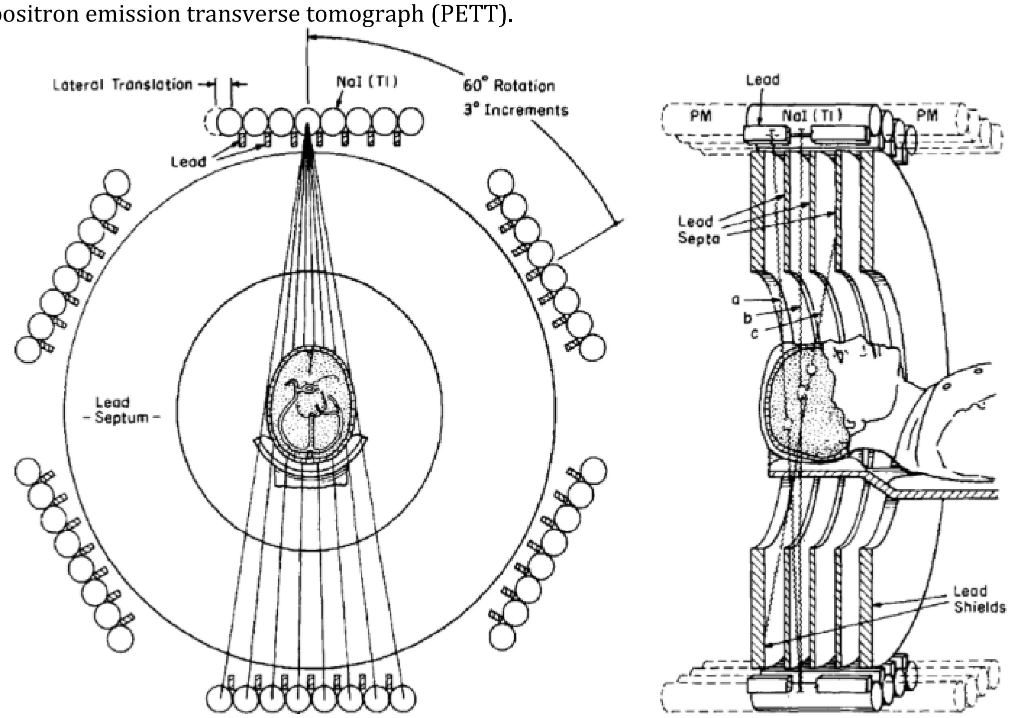
The Massachusetts General Hospital positron camera. (Reprinted courtesy of Gordon L. Brownell and the Physics Research Laboratory at Massachusetts General Hospital.)

VII. POSITRON EMISSION TOMOGRAPHY (PET)

As Ter-Pogossian reported, It became apparent that for tomographic imaging, the annihilation radiation exhibited three major advantages over gamma rays: (1) the coincidence collimation of the annihilation radiation is a more efficient process than the collimation by absorption of gamma rays, (2) the coincidence detection of the annihilation photons allows a very accurate compensation for the attenuation of the radiation in tissues, and (3) the iso-response curves for the coincidence detection of annihilation photons are nearly uniform. This was to establish the principles of positron emission tomography.

In the early 1960s, Rankowitz et al. developed a positron scanner which consisted of scintillation detectors designed for coincidence detection, which simultaneously detects two 511 keV photons emitted at 180° through the annihilation reaction of electrons and positrons. Their report, *A Positron Scanner for Locating Brain Tumors* is included in the Appendix of this article.

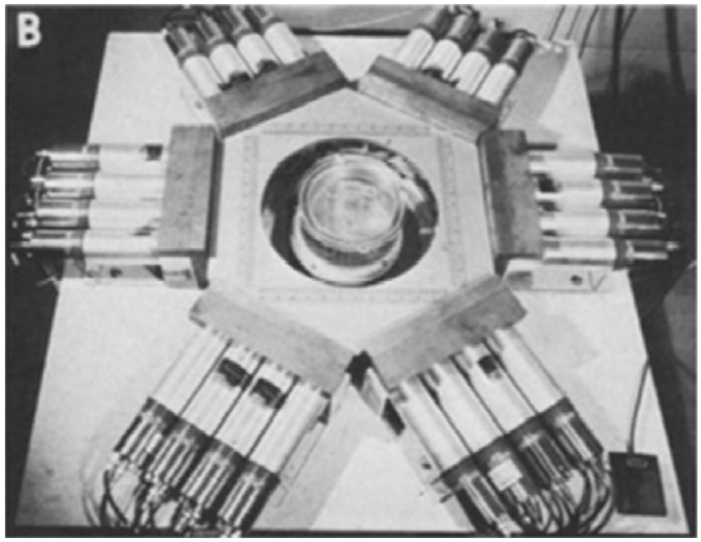
In the early 1970s, Ter-Pogossian's team developed a hexagonal system aiming for clinical human studies, which they named as positron emission transverse tomograph (PETT).



A major feature of the system was the development of fast electronics that were used for precise time-of-flight measurements that could identify and record the two annihilation photons from a specific positron interaction. This was used to determine the location of the position along a line between two detectors. By combining the positions along several lines between pairs of detectors, images could be reconstructed showing the distribution of the positions within a slice of tissue.

This is the fundamental principle of positron Emission tomography (PET).

Some of the initial development was conducted in the laboratory with a prototype using phantoms.



With the development of a system to produce tomographic images of the distribution of positron-emitting short-life radionuclides as shown here, the work continued to create the technology and methods for an expanding range of clinical applications, including whole body imaging and combined imaging with CT. One of the developments contributing to the future systems was the ring configuration of detectors that Dr. Ter-Pogossian is demonstrating here.

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APPENDIX

Author Information

Lawrence N. Rothenberg, Ph.D. is Attending Physicist Emeritus in the Department of Medical Physics at Memorial Sloan Kettering Cancer where he is Director of the Medical Imaging Physics residency program. His main areas of interest in diagnostic radiology have included mammography, computed tomography, and education of radiology residents, medical physics students, and technologists. He is Past President of AAPM, Quimby Lifetime Achievement Awardee, Fellow of AAPM, ACR, ACMP, and HPS, and Distinguished Emeritus Member of NCRP.

Dr. Perry Sprawls

Perry Sprawls, Ph.D., is a clinical medical physicist and educator with a major interest in the preservation of the history and heritage of medical physics and related medical applications. Links to his other historical publications are on the website. www.sprawls.org Contact: sprawls@emory.edu

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THE RISE AND FALL OF THE RECTILINEAR SCANNER IN NUCLEAR MEDICINE

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The first use of localizing organs in Nuclear Medicine was with a probe. It consisted of a lead collimator for localization (not to be confused with the lead grid used to reject scatter in radiography / fluoroscopy). For quantification of thyroid uptake a standardized collimator was developed[1] in order to replicate the thyroid uptake around the world. To obviate the effects of the inverse square law a minimum distance from the face of the detector was required. When a GM probe was used there was no energy information available and the use of a filter was used to account for scatter (the lower energy scatter preferentially absorbed by the filter). The effects of scatter had to be accounted for and eventually were overcome by energy selection of the full energy response. The Compton scatter at lower energies must be rejected with the use of an energy discriminator commonly referred to as a pulse height analyzer (PHA). This is depicted in figure 1 where the photopeak of ^{99m}Tc is shown centered about 140keV while the Compton scatter and patient scatter of the spectrum is shown to the left at lower energies. The PHA window selecting only events from the photopeak to be included in the study is depicted by the vertical lines at 126 and 154 keV which constitutes a typical 20% window.

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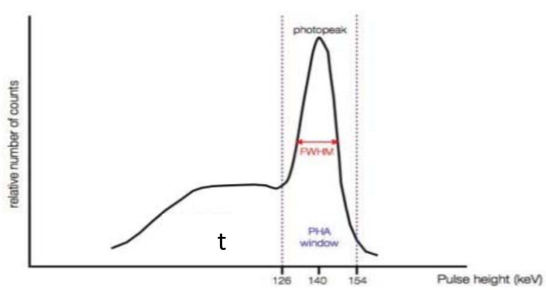


Figure 1. A stylized energy spectrum of a typical ^{99m}Tc isotope including patient scatter which must be removed and was done by the PHA in nuclear medicine.

Probes were also used to give the time varying activity in organs, both for diagnostic work and importantly for radiation dose estimates. The use of two probes was very common to produce renograms of the kidneys.

A need existed for better definition of the organ. In order to address this need, the rectilinear scanner was invented by Benedict Cassen. A picture of this scanner is shown in figure 2.[2]

Figure 2. A photograph of the original Cassen rectilinear scanner shown on the right above the patient.

It required a significant change in the collimator to obtain better definition of the organ. The detector/collimator was transported over the patient to set up the field of view(FOV).. The collimator consisted of multiple conical shaped holes, all whose apexes were at a fixed point. An image of the assembled head of a scanner is shown in figure 3.

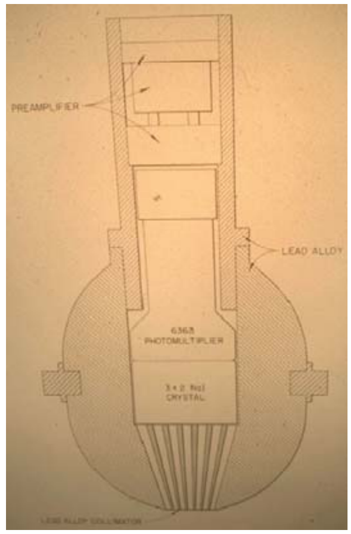


Figure 3. A typical early detector/collimator assembly for a rectilinear scanner for nuclear imaging. Included is the focused collimator on the front of a then typical 3” diameter crystal. Final designs settled on 5” diameter crystals prior to end of scanner development.

There were multiple conical holes separated by sufficient septal thickness of lead to preserve the integrity of the hole at the energy of the gamma ray used. The side of the holes need not have been circular, but the conical nature is required. This gives rise to a tomographic field of view with the spatial resolution being best at a distance from the face of the collimator. Therefore, a focal zone existed where the spatial resolution was satisfactory.

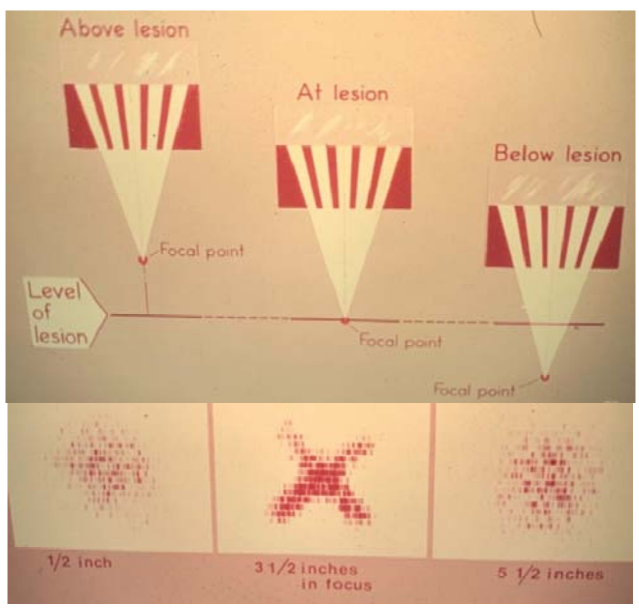


Figure 4. Top image depicts the focal or tomographic plane for a focused collimator. While the bottom image is an acquisition made of a planar radiation target in the shape of an X on the left above the plane of focus, middle in the plane and right below the plane. You can easily observe the natural blurring above and below this plane on the left and right while superior resolution at the plane of focus.

Thus "if the image was clear, it was at the focal zone" as shown in figure 4. This is to be contrasted with the scintillation camera, where the holes are parallel and aren't conically placed. The spatial resolution of the camera using a parallel hole collimator is best at the surface and getting worse as you go away from the surface in contrast to the focal zone of the scanner's collimator. This very important point is shown in figure 5. Notice also included in figure 5 is a method employed in some instances to elongate the tomographic plane of view of the scanner by making the edges of the collimator holes as parabolic rather than straight while maintaining the lateral resolution at the plane of focus.

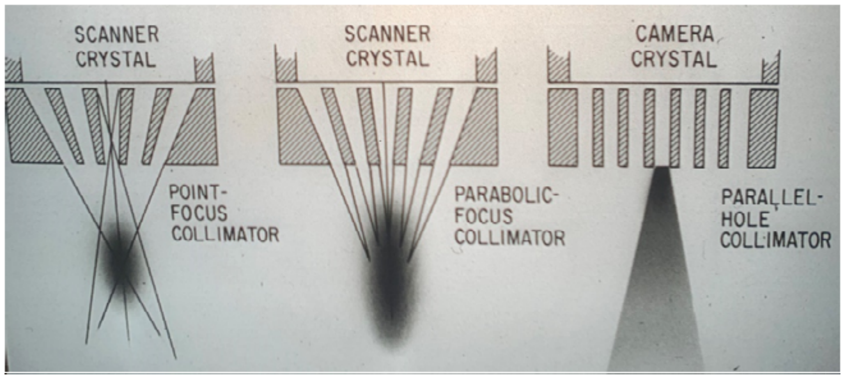


Figure 5. A comparison on the left and middle of a focused and parabolically focused collimators(used on scanners) to that of a parallel hole collimator(used on cameras). The focal or tomographic plane of acquisition was determined by the distance of the scanner detector from the patient while the cameras best resolution was at the face of the camera collimator.

The second very important point is that the field of view (FOV) of a scanner is set up by the scanning motion and can be quite large. The image was produced by moving the probe over the patient in a rectilinear fashion with the use of two motors. The motion in one direction across the patient was smooth while the motion in the other was a step, giving the rectilinear patterns. Initial scanners had a only one detector above the table while later scanners had detectors above (anterior projection) and below (posterior projection). This is depicted in figure 6.

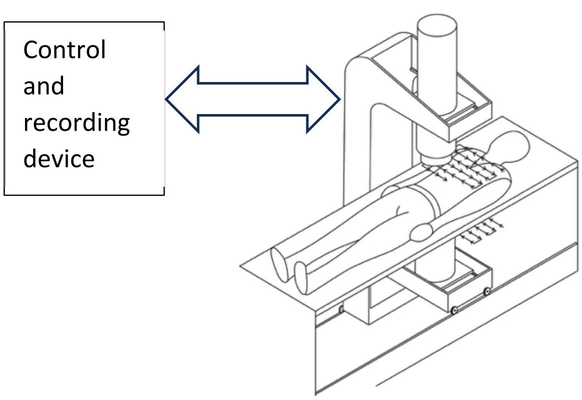


Figure 6. A generalized representation of a rectilinear scanner with a detector shown on the top and bottom of the patient. The detectors as shown would move laterally across the patient and then step to the next line and so on until the entire desired FOV would be covered. The detectors would be connected either mechanically in early devices to a dot making device recording either to paper or film and later electrotonically to some photoscanning film recording device.

In comparison, the FOV for the camera is setup by the area of the detector/camera head. You must keep this in mind when you consider the demise of the scanner. The essential tradeoff of spatial resolution of the collimator versus sensitivity must be made with both the scanner and the camera. The comparison of the two systems roughly depends on comparison of the sensitivity of the active area of the detector. The detector/collimator of the scanner was attached to the readout (either physically in the beginning and electronically in later vintages). In the case of the early scanners this was a physical arm connecting the detector to a device that could tap on a recording medium such as paper which by its nature gave a 1:1

representation of the organ being imaged, which gave a very useful additional property of the scanner in that your could directly determine the organ size as shown in figure 7.

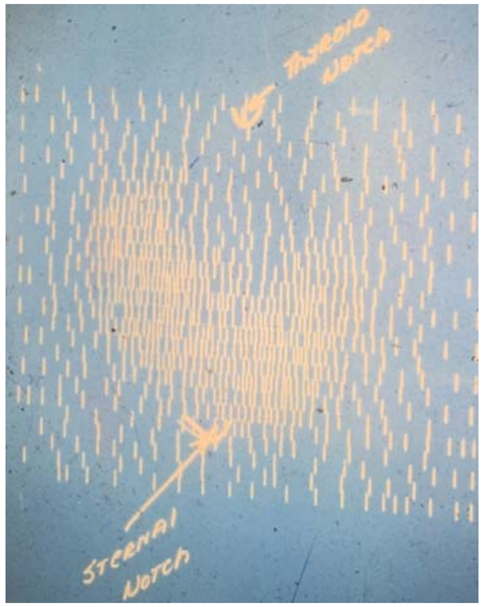


Figure 7. a paper recording of a thyroid using a mechanically coupled recording device to the scanner detector, where dots represent gamma events detected within the selected energy window and measurements could be made with a ruler directly.

The sensitivity of the scanner for single detector scanners was limited by the diameter of the crystal (5" diameter x 2" thick NaI(Tl)). The 5" diameter was limited by the focal zone in distance from the collimator and vertical size of the focal zone. The 2" thickness was sufficient for energies of ^{131}I and even higher energies. In contrast, the modern scintillation camera's 3/8" thick crystals are sensitive at low energies, such as that emitted by ^{99m}Tc, and very insensitive to higher to medium energies (<400 keV) e.g. ^{131}I. A comparison of this whole-body images from a scanner and a camera illustrates these points in figure 8.

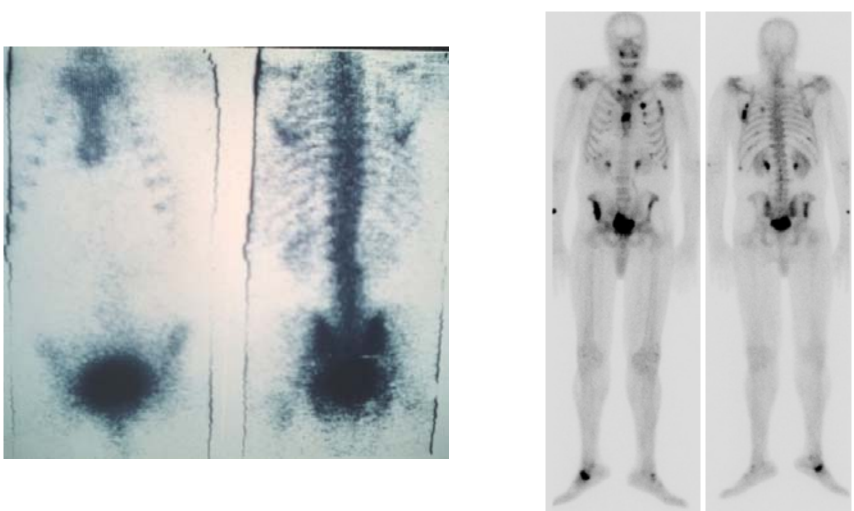
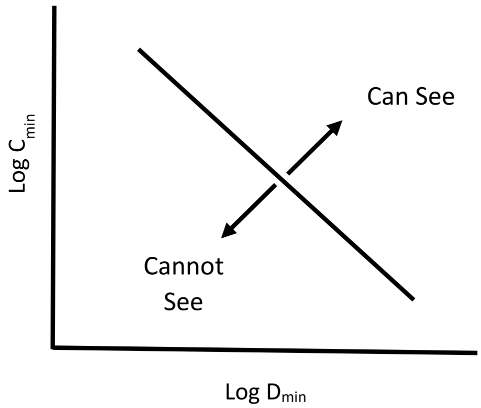


Figure 8. A whole-body exam both AP/PA for a scanner on the left and camera on the left.

While it is obvious which camera image is AP and PA, the scanner images are dependent on the operator putting the focal zone in the correct place for the scanner assuming this is physically possible given the mechanical nature of the detector and table. As discussed earlier, the rejection of scatter is essential in nuclear imaging. For the scanner, the PHA is fed into a count rate meter which along with the speed of the motor and output size produces the image. Thus, the image is a representation of counts/area in the image. The camera output is also in counts/area. Figure 9 shows the significant effect of this statistical nature of the image upon perception. As depicted on the right even with a sufficiently large diameter object the observer is contrast limited by the low count density.



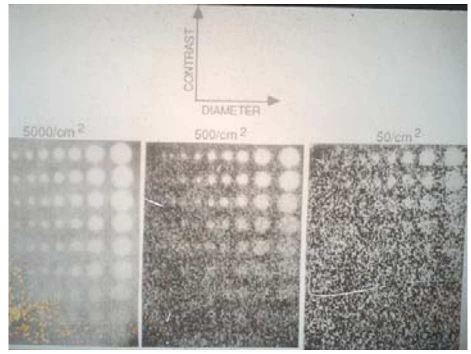


Figure 9. Depicts the limiting nature of statistics on observable contrast versus resolution in nuclear medicine. Depicted on the right is an old slide of a test phantom used in nuclear medicine showing how the observer becomes limited to identify larger diameters based on lower counts densities. This is graphically explained on the left.

This perception is most affected at low contrast. The advent of the scintillation camera[3] spelled the doom of the scanner. The area of the scintillation camera not only provided a means by which to view a large organ "in total" at the same times, allowing dynamic studies, but also increased the sensitivity. This efficiency gain was dependent on the use of ^{99m}Tc. The adoption of kits for ^{99m}Tc happened at the about the same time as the use of the camera, and worked in the favor of the camera. A useful timeline of these events is included at the end of this paper. The bone scan held on for a long time until the advent of the even larger area FOV cameras. While there were intermediate size cameras before the cameras of today, but as shown in figure 10 the intermediate cameras were of sufficient size to "stitch" together an adequate set of spot views which with the superior sensitivity of the camera was deemed better than the scanner.

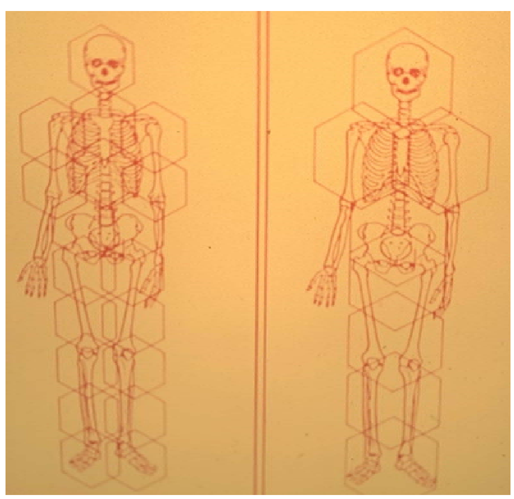


Figure 10. The whole body scan using older cameras by doing multiple spot images of the body on the left a smaller camera than on the more practical right side is depicted.

There was an attempt to use the tomographic imaging in a single direction with a rectangular detector, but the camera still won the day. When a moving table and the multi format images were introduced the increase in sensitivity was maintained and the "whole" bone scan was visible in one image for the camera. Thus, even the bone scan disappeared with the expanded availability of new ^{99m}Tc radiopharmaceuticals. The use of the rectilinear scanner ended and the Anger scintillation camera took its place.

Keep in mind the significant differences

1) The area of the detector of the camera won the day
2) The spatial resolution of the systems are different.
    1. Camera is best at the surface and gets worse as you move away from the surface. The patient must be as close as possible to the collimator
    2. The scanner has a focal zone of acceptable resolution at a distance from the surface of the collimator. This must be placed at what you want to see.
3) The FOV of the camera is set by the area of the detector. A moving table must be used to obtain whole body contiguous images. The FOV of the scanner is set by the scanning motion and can be quite large, e.g., whole body.
4) Scanners were more efficient with ^{131}I but the use of ^{99m}Tc obviated this factor.
5) The acquisition time for cameras was far superior than scanners especially as camera sizes increased.

Historical Timeline [4]

1950 K.R. Crispell and John P. Storaasli used iodine-131 labeled human serum albumin (RISA) for imaging the blood pool within the heart.

1950 Abbott Laboratories sold the first commercial radiopharmaceutical, iodine-131 human serum albumin (RISA).

1951 The U.S. Food and Drug Administration (FDA) approved sodium iodide 1-131 for use with thyroid patients. It was the first FDA-approved radiopharmaceutical.

1951 Benedict Cassen, Lawrence Curtis, Clifton Reed and Raymond Libby automated a scintillation detector to "scan" the distribution of radioiodine within the thyroid gland.

1954 David Kuhl invented a photorecording system for radionuclide scanning. This development moved nuclear medicine further in the direction of radiology.

1955 George V. Taplin used iodine-131 labeled rose bengal to image the liver. He also used radioiodinated hippuran to measure kidney function with scintillation detectors.

1957 W.D. Tucker's group at the Brookhaven National Laboratory invented the iodine-132 and technetium-99m generator, making these short-lived radionuclides available at distant sites from the production of the parent radionuclides.

1958 Hal Anger invented the "scintillation camera," an imaging device that made it possible to conduct dynamic studies.

1959 Picker X-Ray Company delivered the first 3-inch rectilinear scanner.

1960 Louis G. Stang, Jr., and Powell (Jim) Richards advertised technetium-99m and other generators for sale by Brookhaven National Laboratory. Technetium-99m had not yet been used in nuclear medicine.

1962 David Kuhl introduced emission reconstruction tomography. This method later became known as SPECT and PET. It was extended in radiology to transmission X-ray scanning, known as CT.

1962 John Kuranz, Nuclear Chicago, delivered the first commercial Anger camera to William Myers at Ohio State University.

1963 The FDA exempted the "new drug" requirements for radiopharmaceuticals regulated by the Atomic Energy Commission.

1963 Henry Wagner first used radiolabeled albumin aggregates for imaging lung perfusion in normal persons and patients with pulmonary embolism.

1964 The FDA exempted the "new drug" requirements for radiopharmaceuticals regulated by the Atomic Energy Commission.

1964 Paul Harper and Katherine Lathrup developed radiotracers labeled with Tc-99m for the study of brain, thyroid and liver.

1970 W. Eckelman and P. Richards developed Tc-99m "instant kit" radiopharmaceuticals. The first one was Tc-99m-DTPA.

1970 The FDA announced that it would gradually withdraw the exemption granted to radiopharmaceuticals and start regulating them as drugs. The change would be completed by January 20, 1977.

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HISTORY OF PIONEER WOMEN IN MEDICAL PHYSICS

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Abstract:
In celebration of the 60th Anniversary of the International Organization for Medical Physics (IOMP), it is important to recognize and acknowledge women who have made great contributions to the advancement of medical physics (MP). The authors believe that contributions of outstanding female medical physicists in IOMP Regional Organisations may inspire young women to enter medical physics profession. This is especially important for the benefit of future female medical physicists who wish to participate in improving status of women medical physicists worldwide. In this pursuit, young female medical physicists need to be mindful of experiencing some challenges and obstacles in reaching their potentials. The paper discusses developments in the period before 2018 and lists bios of some pioneering women medical physicists from the Regional Organizations of IOMP.

Keywords: Physics, Medical Physics, Medical Engineering, Science, Women Medical Physicists, IOMP, AAPM

1. Introduction:

Physics is not a list of facts about the world. History is not a list of names and dates of what happened in the past. It can be a powerful tool to illuminate the path to future. Scientists adopt and adapt various approaches as new challenges arise. Contributions of scientists are built on the shoulders of those who came before them. They have a role to play in making our world healthier. Each leader identified a problem they wanted to solve and developed a plan to do so.

The history of Medical Physics (MP) is short relative to that of most recognized academic and professional specialties. The rapid growth of Hospital Physicists Association (HPA) in UK in 1940s and American Association of Physicists in Medicine (AAPM) in 1958, led to the formation of International Organization for Medical Physics (IOMP) in 1963. With establishment of European Federation of Organizations for Medical Physics (EFOMP-1980), Association of Latin American Physicists in Medicine (ALFIM-1984), Asia-Oceana Federation of Organizations for Medical Physics (AFOMP-2000), South-East Asian Federation of Organizations for Medical Physics (SEAFOMP-2000), Middle East Federation of Medical Physics (MEFOMP-2009), and Federation of African Medical Physics Organizations (FAMPO-2009), currently IOMP includes about 30,000 medical physicists globally [81].

During the first 30 years after the establishment of IOMP (1963-1993), the number of medical physicists worldwide grew from c.6,000 to about 12,000 members worldwide. However, during this period, the leadership of the Organization (with elections each 3 years) did not include women.

In 1994 IOMP leadership included Ann Dixon-Brown, (UK) as Treasurer and Azam Niroomand-Rad (USA) as Editor-in-Chief of the IOMP Bulleting Medical Physics World. In 1997 IOMP elected Azam Niroomand-Rad as Chair of the Education and Training Committee (ETC). In 2000 Azam was elected as IOMP Vice-President and Nisakorn Manatrakul (Thailand) was elected as Treasurer. In the period 2003-2006 Azam Niroomand-Rad took the position as the first woman President of IOMP. One of Azam most important activities was working with ILO (International Labor Organization) towards recognition and inclusion of Medical Physicists in the International Standard Classification of Occupations (ISCO-2008) – an activity of special importance for the acceptance of the MP profession in many countries. This admission opened many doors to women medical physicists (WMPs) in Health Professionals and health services in developed and developing countries.

During the following years the number of women in the leadership increased and in different periods important IOMP Committees were chaired by women: Science Committee (SC) by Caridad Borrás (Spain, USA); Education and Training Committee (ETC) by Anchali Krisanachinda (Thailand) and Maria do Carmo Lopes (Portugal); Awards and Honours Committee (AHC) by Simone Kodlulovich Renha (Brazil); Medical Physics World Board (MPWB) by Virginia Tsapaki (Greece), Magdalena Stoeva (Bulgaria), Chai Hong Yeong (Malaysia); Professional Relations Committee (PRC) by Simone Kodlulovich Renha (Brazil). Moreover, Dr Borrás (Spain, USA) and Dr Simone Renha (Brazil) supported many activities in development of the MP profession in Latin America.

Since then, Dr Krisanachinda (Thailand) was one of the main contributors for the development of the profession in South-East Asia. Dr Tsapaki (Greece) and Dr Stoeva (Bulgaria) moved the IOMP Bulletin Medical Physics World (MPW) to new heights and increased dramatically its readership. They both played a very important role for the establishment and promotion of the IOMP Women Sub-Committee (WSC) in 2014. Dr Tsapaki became the first Chair of the WSC and Dr Stoeva prepared WSC website. In 2016, during the International Conference of Medical Physics (ICMP 2016, Bangkok) the IOMP WSC organized two women symposia. In 2018, several activities and Webinars were organized by IOMP Women Sub Committee (WSC).

During 2015-2018 the IOMP leadership (ExCom with 11 elected members, President S Tabakov) included four women with Dr Virginia Tsapaki (Greece) as the first woman IOMP Secretary-General; Dr Anchali Krisanachinda (Thailand) as Treasurer; Dr Simone Kodlulovich Renha (Brazil) as Chair AHC, and Dr Magdalena Stoeva (Bulgaria) as Chair of MPWB.

In 2012, the IOMP ExCom established the International Medical Physics Day (IDMP) which was decided to be celebrated on 7 November each year in honor of Maria Skłodowska-Curie (her birthday being on Nov. 7, 1867). The first celebration of IDMP was in 2013, in connection with the IOMP 50th Anniversary of IOMP, which included a special poster with her photo, as a patron of the profession. The IDMP in 2017 was a special celebration of the 150th Birthday of Marie Curie.

Despite this steady growth, the number of female medical physicists in leadership roles was small. This article traces the first steps of promotion of women in medical physics (WMP) in IOMP and its Regional Organizations. Importantly this article also includes is a review of female scientists who made major contributions in physics with application to medicine and medical physics, as well as leading women scientists medical physicists who contributed to the global advancement and development of the MP. These leaders served (and are serving) as role models to generation to come after them.

2. Life and Achievements of Women Scientists in New Physics

2.1 Maria Skłodowska-Curie Polish and naturalized French physicist and chemist (Nov. 7-1867 – 1934). She was the first woman scientist who received Nobel Prize in Physics (1903) and in Chemistry (1911) – hence the first woman (and the first scientist) who received two Nobel Prizes.

Maria Skłodowska-Curie was born in Warsaw, Poland in 1867. She is an inspiring scientist to many female scientists who came after her. Maria entire life, from the very beginning of her scientific career, exemplifies profound struggles and many obstacles that she had to overcome in her life in Poland, in her journey from Poland to France and her life in her adopted country. She wanted to understand the laws of nature that led to the discovery of new elements and eventually the creation of a new branch of science, radioactivity, a term that was coined mainly by her. She was a genius believing “Nothing in life is to be feared – it is only to be understood.”

In 1903, Curie became the first woman to earn a PhD in physics and the first woman to become professor in France. The professors who reviewed Maria’s doctoral thesis about radiation, said “it was the greatest single contribution to science ever written”. However, being a female, she was not allowed to present the result of her research, to the French Academy of Sciences. She never stopped her scientific work and declined to apply to the Academy since it was not open to women.

Marie Curie became the chair of physics at the Science Faculty of the University of Paris after the sudden death of her husband Pierre Curie in 1906. Her scientific research (1986-1909) was under difficult laboratory condition, but when she received her first Nobel Prize in physics (1903, shared with P Curie and H Becquerel), her working conditions gradually improved during 1909-1915. When she received the second Nobel Prize in chemistry (1911), she headed the Radium Institute in Paris (1915-1934), overseeing physics and chemistry research.

Marie Curie published her famous book “The Treatise of Radioactivity” in two volumes that were valuable textbook for young researchers. This led to rapid development of science of radioactivity. Marie Curie’s last great work was her third book “Radioactivity”. Under Maria Curie’s leadership, the Institute of Radium in Paris rose to a leading position in the development of the science of the radioactivity of matter and structure of the atomic nucleus.

When appraising Marie Curie's own work and those done under her supervision, it is clear that she was able to master extensive knowledge in both physics and chemistry. Within less than 25 years after the discovery of polonium and radium, several radioactive elements were discovered in uranium-radium series, thorium series, and actinium series. One of Marie Curie's greatest admirers was Albert Einstein who said "Not only did she do outstanding work in her lifetime, and not only did she help humanity greatly by her work, but she invested all her work with the highest moral quality. All of this she accomplished with great strength, objectivity, and judgement. It is very rare to find all these qualities in one individual."

During World War I (WWI, 1914 -1918), Marie Curie faced new challenges. Marie was a patriot and used the money from her second Nobel Prize to buy war bonds to support the French army. She recognized that wounded soldiers were best served if operated as soon as possible. She saw a need for field radiological centers near the front lines to assist battlefield soldiers. After a quick study of radiology she prepared a vehicle with X-ray equipment and auxiliary generator and created mobile radiography units, known as *petites Curie* ("Little Curies").

In 1920, Marie Curie granted a rare interview in her laboratory in Paris to Mrs Meloney, who was editor of the USA journal - *The Delineator.* During this meeting, Mrs Meloney learned that Marie Curie who had freely given radium away for patients to be treated, had no financial means to acquire additional radium to continue her laboratory research. Mrs Meloney promised Maria to help. When she returned to US, she launched extensive campaign to raise money ($100,000) from the Women of America.

On May 12, 1921, Marie Curie accompanied by her two daughters, Irene (24) and Eve (17) came to USA and they were greeted by Mrs Meloney. On May 20, 1921, at invitation of President Harding, she went to the White House to receive the gift of 1 gram of radium from President Harding. The hazardous source itself was not brought to the ceremony and instead, she was presented with a certificate and a golden key to a safe box with 1 gr of radium. Marie Curie died in 1934 of aplastic anemia, most likely of exposure to radiation and X-rays in pursuit of her scientific research and work in hospitals during WWI. Marie Curie was the first woman to be buried in the Panthéon in Paris on her merit. [1, 2, 3, 4, 5, 6]

2.2 Irene Joliot - Curie (1897-1957) – French Chemist, Nobel Laureate (1935)

Irene was born in Paris in 1897. She was the older daughter of Maria and Pierre. She was 8 years old when she lost her father in a tragic accident. Irene was not told what happened to her father until after his funeral. Maria sense of self-respect and hard work was transferred to Irene. When WW1 started, Irene, a young teenage, accompanied her mother and took part in the war-related activities described above.

After WWI, Irene returned to Paris and worked as her mother's assistant at the Radium Institute. In 1925, Irene received her doctorate. Her doctoral thesis was on alpha particles emitted by radioactive polonium during its disintegration. In particular, she focused on how alpha particles decelerate while moving through matter. Irene 's expertise in dealing with this element was exclusive. Her dissertation defense made it to international News media.

Soon after the discovery of radium in 1903, the Curies observed that all substances close to a strong radium sample became active. They referred to this phenomenon as *induced radioactivity.* When Irene worked at the Radium Institute, she showed that a certain type of nuclear transmutation led to the formation of radioactive species that became known as *artificial radioactivity*.

It was at the Radium Institute that Irene met her husband, Frederic Joliot. Irene and her husband worked together, focusing their research on the atomic nuclei structure. In their experiment, they placed their polonium next to an aluminum foil. They expected hydrogen nuclei to emerge, but instead they observed thar neutrons and positrons appeared. With a Geiger counter, they confirmed that the aluminum foil had become radioactive. Therefore, Irene and Frederic were the first scientists to artificially produce a radioactive element. This discovery had a great impact in producing radioactive materials for cancer treatment.

In 1934, the last year of Marie Curie's life, she knew that Irene and her husband had acquired great fame and repute because of their discovery. In 1935, Irene and her husband received Nobel Prize in Chemistry thus making Maria and Irene the only two mother-daughter pair to have won Nobel Prizes. When Albert Einstein was in Paris, he said "Madam Curie was fortunate to see her work to be continued by her daughter, who was her equal in talent and scientific activity".

In the early 1930s, the whole world started paying attention on French research because of the scientific contributions by Maria Curie, Irene, and Frederic. However, years of working so closely with radioactive materials finally caught up with Irene and she was diagnosed with leukemia. She had been accidentally exposed to polonium when a sealed capsule of the element exploded on her laboratory bench in 1946. Despite this incident Irene continued her work and drew plans for new physics laboratories at Faculty of Sciences in 1955 which is now part of Paris University. Irene and Frederic had two children: Helene Joliot (born 1927) and Pierre Joliot (born 1932). [7, 8, 9, 10, 11]

2.3 Hélène Langevin-Joliot (1927) – French Nuclear Physicist

Hélène Langevin-Joliot-Curie, daughter of Irene Joliot-Curie was born in Paris, France in 1927. She may be a descendent of one of the most honored families in the history of science. Hélène professional contributions to the scientific world have rightly earned her own place in history. She is known for her research on nuclear reactions in French laboratories. She was particularly skilled in math and sciences. When growing up Hélène was encouraged by her parents to study physics which is the field she pursued.

In her teens, Hélène studied at the Ecole National de Chimie Physique in Paris. Later she studied at the Institute of Nuclear Physics and Particle Physics at Orsay where she excelled academically. After receiving her bachelor's degree, she began her doctorate in nuclear physics focusing on auto ionization and internal Bremsstrahlung phenomena. In 1948 Hélène married the physicist Michel Langevin (grandson of the physicist Paul Langevin).

In 1949, after receiving her doctorate, Prof Helene Langevin-Joliot worked as researcher at the French National Center for Scientific Research (CNRS), focusing on nuclear reactions. In 1969, Helene became Director of research at CNRS until she retired in 1992. Upon her retirement, she became Emeritus Director of Research at CNRS.

During 1949 – 1957, Prof Hélène Langevin-Joliot worked at the Laboratory of Chemistry and Nuclear Physics at the College de France. During 1957-2008, she worked on nuclear reactions for the Institute National de Physique Nucleaire et de Physique des Particules. Toward the end of her professional career, she worked for the French Government Advisory Committee.

During 1985-1992, Prof Hélène Langevin-Joliot was a member of the Scientific Advisory Group of the Parliamentary Office and Technological Options. She was also a member of the Commission for the Centennial Celebration for the Discovery of Radioactivity. She was also professor of nuclear physics at the Institute of Nuclear Physics at the University of Paris. She is actively involved in encouraging women to pursue careers in scientific fields.

In 1997, when celebrating 100 years discovery of Radium, Azam Niroomand-Rad met Prof Hélène Langevin-Joliot in Nice, France. When Azam asked Hélène if the physics "gene" has been passed on to her children, Hélène smiled and responded, "her son, Yves Langevin (born 1951), is an astrophysicist".

Since 1997 Prof Hélène Langevin-Joliot and Azam Niroomand-Rad have been in communication. In April 2003, Azam invited Hélène to come to USA and give some lectures to medical and medical physicists at Georgetown University School of Medicine, in Washington DC. At the time, Azam also invited Hélène's aunt, Eve Curie (1904-2007) who was living in New York City to come to Washington DC to visit us. When Azam talked to Eve, she found her very active and alert, despite her age. Eve declined Azam's invitation due to some health issues.

On April 11, 2003, Prof Hélène Langevin-Joliot was interviewed by Azam on behalf of IOMP, AAPM, and American Institute of Physics (AIP), Center for History of Physics at College Park, Maryland, USA. The video interview is available at AAPM Heritage Archive. A few years later in 2009, when Azam Niroomand-Rad received IOMP **Maria Skłodowska-Curie** Award at World Congress in Munich Germany, Hélène invited Azam to her home in Paris. Hélène enthusiastically shared many fond memories of her parents and grandparents at her home. Hélène also took Azam for a visit of Curie laboratory in Orsay Paris. [12, 13, 14, 15, 16]

2.4 Lise Meitner (1878-1968) – Eminent Austrian-Swedish physicist

Lise Meitner received her doctorate in physics from the University of Vienna in 1906 and was the second woman to earn a doctorate in physics. She spent most of her scientific career in Berlin, Germany, where she was a physics professor and a department head at the Kaiser Wilhelm Institute. She was the first woman to become a full professor of physics in Germany. She lost her position in the 1930s because of the rise of anti-Jewish Nuremberg Laws of Nazi Germany.

In 1938 Prof Lise Meitner fled to Sweden, where she lived for many years, ultimately becoming a Swedish citizen. In 1939 Lise Meitner published her discovery that atomic nuclei split during some uranium reactions. She was the first to describe and coin the term "*nuclear fission*" in her scientific paper. Prof Lise Meitner groundbreaking research led to understanding of nuclear fission and eventually to design of the atomic bomb - hence she was known as "Mother of Atomic Bomb".

Prof Meitner was nominated numerous times for the Nobel Prize (in physics and chemistry) by many eminent scientists, but did not receive Nobel Prize. Prof. Lise Meitner is among those most often cited as having been unfairly overlooked. Albert Einstein once called her the "*German Marie Curie*."

Sadly, Prof Meitner was rarely lauded for her critical contributions to physics and chemistry at the time of their novelty. Despite not having been awarded the Nobel Prize, she was invited to attend the Lindau Nobel Laureate Meeting that was founded in 1951 in Lindau, Germany. She received many honors, including the name of element meitnerium (Mt) with atomic number 109 that had similar properties as iridium. After Prof Meitner death in 1997, International Astronomical Union (IAU) named a Crater in Venus in her honor. [17, 18, 19, 20]

2.5 Maria Goeppert Mayer (1906-1972) – German American Physicist, Nobel Laurate (1963)

Maria Goeppert was born in Kattowitz, Germany in 1906. She grew up in Gottingen, Germany where her father was a pediatrics professor at George-August Universitat. Maria was very close to her father who encouraged her to pursue higher education. In 1914, when she was 8 years old, WWI (1914-1918) started and hence there was a shortage of food. But when WWI ended, Maria was a young woman ready to resume her education. Even though Maria excelled in mathematics, her teachers doubted if Maria could go to university.

However, in 1924, Maria Goeppert became more interested in physics especially after she met Max Born, a theoretical physicist who was developing quantum mechanics. Max Born encouraged Maria to take physics courses which she did until she finished her doctorate in 1930. During this period, Maria faced financial difficulties especially after her father died. Despite many hardships, Maria was happy to meet her future husband, Joseph Mayer, an American researcher from California, who was at Göttingen to study quantum mechanics. Maria's husband did not want her to quite her career after marriage.

Before and during World War II (WWII, 1939-1945) Germany was under Nazi dictatorship. Therefore, Maria and her husband had to move to Baltimore, Maryland, USA. However, Maria could not get a position at John Hopkins University where her husband was employed. Moreover, Maria's life became more difficult when her children were born in 1933 and 1938.

With rise of WWII-related sentiments in USA, Maria's husband lost his job at John Hopkins. But soon after he was employed to teach chemistry at Columbia University in New York City, NY. Maria was also employed to teach mathematics and work for Manhattan Project group that were doing research and development. They produced the first nuclear weapons and created atomic bomb. Maria's work was to design an efficient way to separate uranium-235 from uranium-238.

When WWII was over in 1945, Maria worked at the Institute for Nuclear Studies at the University of Chicago in Illinois. She studied why some isotopes were more stable than others. In 1960 when family moved to California, Maria at age 53, finally became a professor at the University of California in San Diego, CA. Maria continued her research in double-photon emission theory, that was the subject of her doctoral thesis.

In 1956, Prof Maria Goeppert Mayer became a member of the National Academy of Sciences in the USA and a corresponding member of the Akademie der Wissenschaften in Heidelburg, Germany. In 1963 Maria Goeppert Mayer received the Nobel Prize in physics for proposing the nuclear shell model of the atomic nucleus. Maria died in 1972 in San Diego. Later, in Maria's honor, an award was created under her name by the American Physical Society for young women physicists [21, 22, 23, 24].

2.6 Rosalyn Yalow (1921-2011) – American Nobel Laureate in Medical Physic (1977)

In 1921 Rosalyn Yalow was born to Jewish parents in the toughest neighborhood of Bronx in New York City, NY. She studied physics at Hunter College in New York City. She then worked as a secretary for Dr. Rudolf Schoenheimer who was a leading German American biochemist in Columbia University College of Physicians and Surgeons. She also worked as a secretary to Michael Heidelberger who was a famed biochemist working in immunology.

A few years later, Yalow was offered a teaching assistant position in physics at the University of Illinois at Urbana-Champaign. She received this offer partially because WWII (1939-1945) had just begun, and many men had to go to war. The University decided to admit women and offer them education and jobs to avoid shut down.

Yalow was the only woman among the department's 400 members and the first woman since 1917. Being surrounded by gifted men made her aware of a wider world in science. They recognized her talent, encouraged her, and supported her to succeed. However, Yalow felt that some women did not like her research ambition in physics since she did not want to be schoolteacher, the usually acceptable path for a woman in science at the time.

In 1945 Yalow earned her PhD at the University of Illinois at Urbana-Champaign. In 1946, she returned to Hunter College in NY to teach physics at the New York University. Her first job was an assistant electrical engineer at the Federal Telecommunications Laboratory. She again found herself to be the only woman employee. She remained a physics lecturer from 1946 to 1950. In meanwhile in 1947, Yalow began her long consulting association with the Bronx Veteran’s Administration (VA) Hospital that were interested in establishing research program for medical uses of radioactive substances. Finally, Yalow left her teaching job and became a fulltime researcher at the VA in 1950.

At the Bronx VA Hospital she developed radioimmunoassay, a radioisotope tracing technique for measurement of tiny quantities of various biological substances in human blood as well as a multitude of other aqueous fluids. Without Yalow contributions in accurate hormone measurement, it was impossible to diagnose various hormone-related conditions and endocrine diseases like type 1 diabetes. Despite its huge commercial potential, Yalow refused to patent the method.

In 1968, Yalow was appointed as a research professor in the Department of Medicine at Mount Sinai Hospital, where she later became the Solomon Berson Distinguished Professor at Large. Yalow had a passion for the next generation of researchers, and she was a mentor figure to scientists from around the world, many of whom came to share her passion for investigative endocrinology research. In this way, Yalow's legacy in endocrinology was carried on and she was referred to as "The Mother of Endocrinology."

Prof Yalow received many awards from various organizations including Award from the American College of Physicians recognizing her contribution to internal medicine. In 1972, Yalow was awarded the William Middleton Award for Excellence in Research, which is the highest honor awarded annually by the Biomedical Laboratory Research and Development Service to senior biomedical research scientists in recognition of their outstanding scientific contributions and achievements, pertaining to the healthcare of veterans. In 1972, Yalow received the Koch Award of the Endocrine Society, that was designated for individuals for dedication to excellence in research, education, and clinical practice in the field of endocrinology.

In 1977, Yalow was the fourth female scientist and the first American-born woman, to receive the Nobel Prize in a scientific field. She was also the second woman in the world to receive Nobel Prize in the physiology or medicine category - the first was Gerty Cori who received Nobel Prize in 1947.

Prof Yalow also received the Golden Plate Award of the American Academy of Achievements. In 1978, she was elected a Fellow of the American Academy of Arts and Sciences. In 1986, Yalow was awarded the A. Cressy Morrison Award in Natural Sciences of the New York Academy of Sciences. In 1988, Yalow received the National Medal Award that is given to an American who deserve the highest honor in science and technology. In 1998, Prof Yalow was inducted into the National Women’s Hall of Fame. In 1998 Prof. Yalow was interviewed by Prof Azam Niroomand-Rad and Prof. Robert Gorson at her home in New York City, NY. [25, 26, 27, 28]

3. Pioneering Women from North America with Leading Roles in Advancement of Physics as applied to Medical Physics

3.1 Harriet Brooks (1876-1973) – First Nuclear Physicist in Canada

Harriet Brook was born in 1876 in Exeter, Ontario, Canada. Harriet's father was struggling to feed his family and provide education to his nine children. Only Harriet and her younger sister were able to continue their education after high school. In 1894 when family settled in Montreal, Harriet completed her education at the Seaforth Collegiate Institute in Seaforth Ontario. Harriet's mother encouraged her to pursue her education and to enroll in McGill University in Montreal.

Harriet was an outstanding student and supported herself by winning scholarships and awards every year. At college Harriet studied mathematics for the first two years and physics for the last two years. In 1898, Harriet completed her college education with high honors in mathematics and physics. She was also awarded a teaching diploma that was given to women graduates to be encouraged to become schoolteacher.

Harriet was very talented and right after her college education, she was hired by Ernest Rutherford who had gone to McGill University (from 1897 to 1907) to establish a laboratory for nuclear physics research. Rutherford had become known as "father of nuclear physics" when he had received the Nobel Prize in Chemistry (1908).

Harriet studied radioactive materials at the laboratory in McGill University. When Rutherford returned to England, Harriet followed him and worked under J.J. Thompson at the University of Cambridge. At Rutherford's Cavendish laboratory, Harriet continued her studies on radioactivity and after a year she returned to Canada and joined Royal Victoria College at McGill University as a tutor in physics.

In 1904, Harriet went to USA and became a faculty at the Barnard College, a women's college that was affiliated to the University of Columbia in New York City. In 1906, Harriet got engaged with a physics professor from Columbia University. But the Dean at Barnard College asked Harriet to resign arguing that "she cannot be both married and a successful academician". Harriet wrote to the Dean saying: "I think it is a duty I owe to my profession and to my sex to show that a woman has a right to practice her profession and cannot be condemned to abandon it merely because she marries". Harriet broke up her engagement and kept on working for one more year at the Barnard College in New York City.

In 1906, Harriet travelled to Paris and became an independent researcher working with Marie Curie at the Institute de Radium in Paris, France. Marie Curie invited Harriet to stay for one more year, but she decided to go to England for a faculty position at the University of Manchester.

In 1907, when Harriet returned to Canada, at the age of 31, she married a wealthy engineer of the Montreal Power and Water Company who was a former physics instructor at McGill University. After marriage, Harriet stopped working raising three children; two of whom tragically died in their teens. Harriet Brooks died in 1933 in Montreal at the age of 57 "of a blood disorder" - presumably leukemia caused by radiation exposure.

In Harriet Brooks obituary, New York Times described her as "Discoverer of the Recoil of a Radioactive Atom". Rutherford also wrote a highly laudatory obituary in the Journal of Nature 131 (3320) page 865. He said, Harriet's contributions to physics became recognized as fundamental work in nuclear science. She was the first person to show that radioactive substance emitted from thorium was a gas with molecular weight of 40-100, a discovery crucial to the determination of transmutation of elements in radioactivity decay.

In 2002, 69 years after Harriet Brook death, she was inducted to the Canadian Science and Engineering Hall of Fame. Also, at the Nuclear Research Laboratory at Chalk River laboratories, a building was named after her.

Harriet Brooks legacy is that she was the first Canadian female nuclear physicist. She is most famous for her radioactivity research. She discovered atomic recoil, and transmutation of elements in radioactive decay. Ernest Rutherford, who guided Harriet graduate work, regarded her as comparable to Marie Curie in the caliber of her aptitude. She was among the first persons to discover radon and to determine its atomic mass. [29, 30, 31, 32, 33, 34]

3.2 Edith Quimby (1891-1982) - First Woman Medical Physicist in the USA (AAPM - established in 1958)

Edith Quimby was born in Rockford, Illinois. She studied at the University of California and was awarded MSc degree in physics in 1916. She was appointed assistant physicist to Gioacchino Failla at the Memorial Hospital in New York City in 1919 - thus, making her the first woman to be appointed as a medical physicist in the AAPM. Edith developed a widely employed dosimetry system for single plane implants with radium and radon seeds. This is widely known as the Quimby System, and a dosimetry methodology for internal radionuclides.

Quimby has published the first comprehensive physics textbook for radiologists "*Physical Foundations of Radiology*" (co-authored with Otto Glasser, Lauriston Taylor, and James Weatherwax). She has also published "*Radioactive Isotopes in Medicine and Biology: Basic Physics and Instrumentation*" (co-authored with Sergei Feitelberg). In 1936, she became one of the first physics examiners for the American Board of Radiology (ABR) and served as President of the American Radium Society in 1954.

Prof Edith Quimby is known as founder of Nuclear Medicine. She developed diagnostic and therapeutic applications of X-rays. When she moved to New York City and worked at Memorial Hospital Cancer Institute, she studied energy emitted by potential materials for nuclear medicine as well as the amount of radiation absorbed by the body from different sources. In 1941 she was appointed to the faculty of Cornell University Medical College in New York as an assistant professor of radiology. The following year, she became an associate professor of radiation physics at the College of Physicians and Surgeons in Columbia University in New York City. In 1954, she was promoted to full professor and retired in 1960.

Prof Quimby has received many awards including the Janeway Medal from the American Radium Society (1940), the Radiological Society of North America (RSNA) Gold Medal (1941), and the Gold Medal of the American College of Radiology (ACMP) in 1963. Dr Quimby was also awarded honorary doctorate degrees by Whitman College in Walla Walla, Washington (1940) and Rutgers University New Jersey (1956). In 1963, Prof Quimby received Gold Medal from the American College of Radiology (ACR). She was one of the first few members of the AAPM Organization. In 1977 Prof Quimby received the AAPM prestigious Gold Medal Award named after William Coolidge. Later in 1966, AAPM established a Lifetime Achievement Award in honor of Prof Edith Quimby.

Prof Quimby has been recognized for her scientific work throughout her career. She became member of several scientific societies. In 1940, she was the first woman to receive the Janeway Medal from American Radium Society for her work in Specification of Doses in Radium Therapy. Prof Quimby is known as "Mother of Nuclear Medicine". She was elected as the first female president of the American Radium Society (1954). One of Prof Quimby research article, released in 1962, was "Late Radiation Effects in Roentgen Therapy for Hyperthyroidism" where she suggested ceasing the use of all Roentgen X-rays in radiation therapy until its long-term treatment effects is better understood. [35, 36, 37].

3.3 Ann Wright (1922-2016) – First Woman Medical Physicist President of AAPM in the USA

Ann E. Wright grandparents moved to NY City from Ireland. She was born in New York City in 1922. In high school, even though Ann Wright was outstanding in mathematics, but the physics teacher would not allow her to take physics courses – "girls could not do physics". However, Ann's math teacher eventually persuaded the physics teacher to allow Ann to sit into his class. But she was not allowed to do any practical physics lab classes involving electricity – "which was too dangerous for girls". Ultimately, however, the physics teacher was softened and gave "D" to Ann.

Upon graduation from high school, Ann received a scholarship to study physics at the University of Houston, in Texas. Unfortunately, Ann had to work for the Shell Oil Company for financial reasons. Initially she did clerical work but soon was promoted to work as an accountant. Recognizing her abilities in math, Shell Oil Company sent her to study computer programming at IBM (International Business Machine). This changed Ann's professional trajectory. However, she could not be promoted at IBM without a college degree. She returned to Shell Oil Company to pursue a BSc degree in Business at the University of Houston. While there, she took a physics course and did so well that her teacher persuaded her to change her major to physics even though she was just two courses short of graduating in Business.

Later, Ann was encouraged by her physics teacher to respond to a job opening at the MD Anderson in Texas to get some additional income. She was interviewed by Prof Bob Shalek who recognized her unique ability in computer programming. He offered Ann a part-time job while completing her BSc degree. Ann helped Marilyn Stovall at MD Anderson to develop a database for brachytherapy data collection analysis and treatment planning calculations.

Eventually in 1951, at age 39, Ann completed her BSc in physics at MD Anderson. Under Prof Bob Shalek leadership Ann received an NCI (National Cancer Institute) scholarship to ultimately completer an MSc and PhD in medical physics. Subsequently, Ann began her career as a medical physicist in Houston and Galveston in Texas.

Dr Ann Wright served as AAPM Treasure (1974-1976). She also served as Chair of the Board of the Chancellors of the ACMP (American College of Medical Physics) in 1984. She received Marvin Williams Award in 1991. She served as AAPM Representative to the AIP (American Institute of Physics) Governing Board Executive Committee. Dr Ann Wright became AAPM President in 1982.

Prof Ann Wright will be remembered, not only as a great leader of the medical physics profession, but as a great role model for young women and men who intend to pursue medical physics profession. The medical physics profession in USA is where it is today in large part due to Prof Ann Wright efforts. Her influence in AAPM will be felt for many years to come. [38, 39].

3.4 Sylvia Olga Fedoruk (1927-2012) - First Woman President of Medical Physics in Canada (Division of Medical and Biological Physics (DMBP): Established in 1946)

Sylvia Fedoruk was one of the pioneers in applying the principles and experimental techniques of physics to improve patient care in Canada. Born in Canora, Saskatchewan, to immigrant Ukrainian parents. She grew up in rural Saskatchewan at Wroxton. She moved to Windsor, Ontario during WWII and there her English teacher encouraged her to pursue a career in science.

After finishing high school, Sylvia completed her Bachelor (1949) and Master (1951) degrees in physics from the University of Saskatchewan. As a campus athlete in the 1940s, Sylvia played basketball, hockey, volleyball, track and field and golf. She won a western Canadian softball championship with the Saskatoon Ramblers in 1955, and Canadian women's curling titles in 1960 and 1961.

Sylvia was academically outstanding and received many scholarships and awards for her excellence. Sylvia was a pioneer in leading-edge cancer research, primarily in the field of nuclear medicine. Sylvia Fedoruk was recognized worldwide for her work in the scientific community. Her area of expertise was medical physics, and she was the only woman in Canada who was researching medical physics in the 1950s. Her biggest activity was her involvement in the development of the Cobalt 60 units for cancer treatment. Sylvia worked on a dosimeter that allowed for greater control over radiation dosage.

Sylvia began her career in 1951 as part of the staff of the University of Saskatchewan. This was where she co-developed the Cobalt 60 Therapy Unit. In 1956 she became an assistant professor at the university and 17 years later in 1973 she became a full professor. She was the first woman elected Chancellor of the University of Saskatchewan in 1986 and she held that post for 4 years. Throughout her life she worked for several different organizations and boards, including the Saskatchewan Cancer Foundation, the Saskatchewan Commission on Direction in Health Care, the Atomic Energy Control Board of Canada, and the International Atomic Energy Agency. She was also the first female trustee of the Society of Nuclear Medicine. In 1988 she was sworn as the first woman Lieutenant Governor of Saskatchewan and held the office until 1994.

Sylvia scientific achievements gave her worldwide recognition and her work will continue to be an inspiration to many scientists. In addition to her tremendous scientific accomplishments, she defied odds and became to the first woman in many activities in Canada.

Sylvia Fedoruk's scientific career helped laying the foundations of use for today's essential diagnostic and treatment technologies including CT (Computed Tomography) and PET (Positron Emission Tomography) scanners. Sylvia calculation tables for radiation treatment became the world standard for depth and dose measurement and remain so to this day. Additionally, as a pioneering woman in the fields of physics and state service, Sylvia Fedoruk's life continues to inspire women to break glass ceilings and all people to strive for excellence.

A pioneering woman of science—one of the few Canadian female medical physics researchers in the 1950s—Sylvia also went on to serve as the university's first female chancellor (1986) and the province's first female lieutenant-governor (1988). At a time when there were few highly placed female leaders in academe, Sylvia excelled as a competitive student-athlete. Her remarkable career touched on many of the scientific, political, and social challenges of her time, including nuclear energy issues, women's equality, and gay rights.

As a graduate student of medical physicist of Dr Harold Johns, Sylvia established the world standard for radiation depth-dose measurements to treat tumors deep inside the body. The cobalt-60 therapy unit was a groundbreaking advance in cancer treatment innovation that positioned University of Saskatchewan to become a leader in areas of nuclear medicine and biomedical imaging that is today.

Sylvia was a strong supporter of women in science. She was the first woman to join the Atomic Energy Control Board of Canada, an advisor to the Federal government on radioisotopes, and a consultant with the International Atomic Energy Agency throughout the 1960s. Due to her national reputation, Sylvia was included in Queen Elizabeth II visit's list in 1977.

In 1986, Sylvia was named the first female Chancellor of the University of Saskatchewan. She was made an Officer of the Order of Canada in 1987. Two years later she was appointed the first Lieutenant Governor of the province. In 2009, Sylvia Fedoruk was inducted to the Canadian Medical Hall of Fame in Montreal, Quebec. In 2011, the Sylvia Fedoruk Canadian Center for Nuclear Innovation was opened. The Center supports nuclear research and manages the Saskatchewan Centre for Cyclotron Sciences.

Dr Sylvia Fedoruk received many Awards & Honors during her 35 years carrier including but not limited to: Queen's Silver Jubilee Medal (1977), Officer of the Order of Canada (1986), Saskatchewan Order of Merit (1986), Honorary DSc, University of Windsor (1987), Honorary Degree, University of Regina (1991), Canada 125th Commemorative Medal (1992), Honorary LLD, University of Saskatchewan (2006). [40, 41, 42]

3.5 Margaret Young (1922-2012): Pioneer Scientist in Canada

Margaret Jane Carr was born in Ealing, London, England in 1922. Following primary school, she was educated at Haberdasher's Aske's School which was evacuated to Dorchester during WWII. She had her physics education at prestigious Royal Holloway College in London, London University England. She received her BSc in 1943 and her MSc in 1949.

In 1942, at the age of 20, while Margaret was working for her physics degree, she was invited to become the youngest founding member of the Hospital Physics Association (HPA) in UK. She continued to work as a lecturer in physics at the Royal Free Hospital (1943 – 1949). While working for her physics degree, Margaret moved to Canada and worked as a physicist at the MRC (Medical Research Council) Radiobiological Research Unit at the Atomic Energy Research establishment (1941 – 1951).

In 1951 Margaret married Dr Young and accompanied him to Ottawa, Canada. Margaret worked as a physicist at the Ottawa Civic Hospital. From 1952 to 1955 Margarete and her husband, Dr Young, retuned to London, UK where Margaret worked at the Charing Cross Hospital, a teaching hospital (established in 1818) in London, UK.

In 1955, Margaret and her husband returned to Canada, and took residency in Vancouver. From 1955 to 1985, Mrs Young was employed as medical physicist by the Cancer Control Institute of British Columbia (now known as the B. C. Cancer Agency: BCCA). Working half time, she did extensive teaching for the nurses (who have now been replaced by therapists for treatment delivery and radiographers). She wrote a textbook titled "Radiological Physics" which is still in use at BCCA today. The first, second, and third editions of this book were published by H. K. Lewis & CO. in London, UK in 1957, 1967, and 1983 respectively.

In addition to the textbook, perhaps Mrs Young is best known for her contribution to medical physics and the work she did on Radium Tables. Mrs Young performed the calculations for converting the in-air dosimetric data to tissue dosimetric data. She worked with a primitive computer in the 1960s to accomplish this work. She was also involved in intra-peritoneal treatment for ovarian carcinoma using ^{32}P and had some involvement with the negative pi meson medical facility at TRIUMF which is Canada's national particle accelerator center and is considered as Canada's premier physics laboratory and world's leading subatomic physics research center.

By 2009, Mrs Young received many awards and honors including Gold Medal from the College of Medical Physics (COMP). In 1978, at the annual meeting of the Canadian Association of Physicists (Division of Medical and Biomedical Physics) in London, Ontario, Margaret Young was acknowledged as one of the six founding members of the Canadian College of Medical Physics. The Youngs remained in Vancouver, where Margaret Young passed away in 2012. [43]

3.6 Chien-Shiung Wu (1912-1997) – An Eminent Early Physicist in the USA

Chien-Shiung was born in Liuhe, a small town near Shanghai, China. When she was growing up in China, there was little opportunity to have a formal education. Her father (accompanied by his daughter) went door to door to recruit students from poor and rich families alike. The goal was to eradicate illiteracy and discrimination against women by giving them good education.

Chien-Shiung was encouraged by her father to pursue an education beyond her hometown. In 1923 at age 11, Chien-Shiung applied to join teacher training program at the Soochow Girl's High School that was a prestigious and highly competitive program in China. In 1929, Chien-Shiung graduated from High School with high grade in her class. From 1930 to 1934, Chien-Shiung studied physics at the National Central University in Nanjing, China, a very competitive school. In 1936, Chien-Shiung went to United States for completion of her education.

Chien-Shiung enrolled at the University of Michigan to pursue her PhD degree in physics. After a week, she changed her mind when she visited the University of Berkely (UC Berkley) in California where she found it to be more liberal than Michigan. When Chien-Shiung physics advisor (Luke Chia-Liu Yuan) received a grant to work at the California Institute of Technology (Caltech) in Pasadena, California, she stayed at the UC Berkley until she graduated in 1940.

After graduation, Chien-Shiung worked with Enrico Fermi, who had made the first US nuclear reactor in Chicago, Illinois. Later Chien-Shiung was invited by Robert Oppenheimer, a theoretical physicist known as "father of the atomic bomb" to give a talk about her latest nuclear fission research at the UC Berkely where she had performed parity conservation experiments in beta decay. By this time Chien-Shiung was known as the "Chinese Marie Curie".

In 1942, Chien-Shiung married Luke and decided to leave UC Berkely where women were not offered teaching positions. Unfortunately, at that time such practices were often seen in the top-20 Universities in USA. Later the role of women was recognized at the Ivy Schools in Eastern USA. Chien-Shiung eventually taught at Smith College, a private women's liberal arts college in Northampton, Massachusetts.

Chien-Shiung and Luke had started their family and stayed in US where it was especially difficulty to return to China during the Japan-China war that erupted in 1937. Chien-Shiung had lost all her contacts with her family in China. When Japan was defeated in WWII, Chien-Shiung went to China and sadly found out that her parents and brother had died.

In 1950s, particle accelerators became popular and new subatomic particles were discovered. The physicists Lee and Yang at Columbia University and Princeton respectively had proposed the idea of parity conservation applied to electromagnetic and strong interactions that did not apply to weak interactions based on the discovery of K-meson particle. Therefore, they needed help from Chien-Shiung to prove their theory. The result of her experiment eventually established parity conversation as a fundamental law of physics.

Even though Chien-Shiung was not considered for Nobel Prize when Lee and Yang received it in physics (1957), Chien-Shiung received many awards and honors until she retired in 1980. She was named "Scientist of the Year" in 1975 and became the first female president of the American Physics Society. In 1978 she received the first Wolf Prize in Physics. She died in 1997 in New York City and her ashes were taken to China and was buried in the courtyard of the Mingde School near Shanghai, China. [44, 45, 46, 47, 48].

3.7 Ellen Elizabeth Grein, El-Khatib, Wilcox (1950): First Woman President of Canadian Organization of Medical Physicists (COMP, Established 1989):

Ellen Elizabeth Grein was born in Heppenheim, West Germany in 1950. From (1973 -1975), Ellen worked as a research assistant under the leadership of Dr. Willi Stahlhofen at the Institute of Radiation and Environmental Research in Frankfurt, Germany. She then moved to Canada and became aware of the field of medical physics. From 1976 to 1979 Ellen worked as electron microscopist in Dr Marc Cantin Laboratory in the Pathology Department of the University of Montreal.

In 1971, Ellen Grein received her BSc in physics from Loyola College, Montreal, Quebec, Canada. She then received her MSc in physics form Concordia University in Montreal, (1980). She was Dr Jerry Battisa first PhD student at the University of Alberta. She completed her PhD in medical physics at University of Alberta, Edmonton, Alberta, Canada (1984). Dr Ellen El-Khatib's first position in clinical medical physics was with Dr Ervin Podgorsak at McGill University in Montreal where she was employed by the Montreal General Hospital as a clinical physicist in 1984.

From 1985 to 1987 Dr Ellen El-Khatib was appointed to an academic position as assistant professor at McGill University in Montreal. From 1987 to 1988, she worked as medical physicists at the King Faisal Specialist Hospital and Research Center in Riyadh, Saudi Arabia. She then returned to Canada and took a position as senior medical physicist at the Cross Cancer Institute in Edmonton, Alberta. At the same time, she had academic appointment as adjunct professor in Physics Department at the University of Alberta.

In 1991, Dr Ellen El-Khatib took a position as senior medical physicist at the British Columbia Cancer Agency (BCCA) in Vancouver, Canada. In 1992, she was appointed Department Head of Medical Physics and Professional Practice Leader for Medical Physics at BCCA. Under Ellen's leadership medical physics at the BCCA grew to become the largest radiation medical physics group in Canada. Since 1991, the number of physicists increased from 9 at two centers to 35 in four centers in 2003. She recruited more than 30 physicists and oversaw the development of essentially three entirely new cancer centers, and a major reconstruction of the Vancouver Cancer Center (VCC) radiation facility. During this time Ellen also oversaw the expansion of the Screening Mammography Program of BC, the establishment of proton therapy at TRIUMF particle accelerator center in Vancouver, BC. She also initiated stereotactic radiosurgery and prostate brachytherapy as provincial programs at VCC.

In addition to facility and program development, Dr Ellen El-Khatib built an academic program in graduate medical physics at the University of British Columbia, from which five PhD students and two MSc students were graduated when she left in 2003. This program obtained AAPM CAMPER (Commission on Accreditation of Medical Physics Educational Programs Accreditation) in 2003.

Later Dr Ellen El-Khatib Wilcox moved to the US and took a position as Chief Medical Physicist at Saint Francis Hospital and Medical Center, in Hartford, Connecticut. Although no longer practicing in academic environment Ellen has remained active in research, clinical development, and mentoring new graduate medical physicists at the start of their careers.

Dr Ellen Wilcox has published numerous articles in national and international journals. In 1991, Ellen received AAPM Travel Award to present papers at the World Congress of Medical Physics in Kyoto, Japan. From 2000-2004, Ellen has served as Associate Editor, Medical Physics Journal. She continued as Reviewer and Guest Associate Editor for Medical Physics Journal. Ellen has been active in AAPM committees and Task Groups: Education and Training of Medical Physicists (1998), Awards Selection Subcommittee, Task Group 1: Revision of Report 44: Academic Programs for MSc Degree in Medical Physics, Task Group 69: Radiographic Film Dosimetry (2001).

Dr Ellen Wilcox became certified in 1985 from the Canadian College of Physicists in Medicine. In 1987, Ellen became Fellow of the Canadian College of Physicists in Medicine (FCCPM). In 2003 Ellen was recognized as Fellow of the American Association of Physicists in Medicine (FAAPM). [49, 50,51].

3.8 Azam Niroomand-Rad (1947) – First Woman President of the IOMP

Azam Niroomand-Rad was born in Tehran, Iran. She studied math and physics in middle school and high school. Recognizing Azam abilities in math and physics, she was encouraged by her math/physics teacher to study physics that was not an ordinary choice for girls in Iran. Being inspired by Maria Skłodowska-Curie personal and professional challenges in Poland and France, Azam applied and won a Fulbright Scholarship to go to USA for her college education in 1966.

Azam excelled in math and physics. She supported herself by receiving scholarships and awards every year. At college Azam studied mathematics for first two years and physics for the last two years. In 1970 Azam received her Bachelor of Science (BSc) with a major in math a minor in physics from the State University of New York, Albany, New York. She, graduating with honors; Summa Cum Laude and Phi Beta Kappa. Azam then went to Michigan State University (MSU) in E. Lansing Michigan and completed her Master of Science (MSc) in physics (1971). When meeting her future husband, Dr Hossein Hamedani, she returned to Iran and taught physics at the Department of Physics at the Arya Mehr University of Technology in Tehran from (1971-1975). Azam and her family then returned to USA and she completed her PhD in Atomic and Molecular Physics at the MSU in 1978.

From 1978 to 1980 Azam and her family returned to Iran and taught physics at the Department of Physics at the Arya Mehr University of Technology in Tehran. Initially, she was excited looking for establishment of a "Government of the people, for the people and by the people". However, when Ayatollah Khomani went to Iran (1978), an authoritarian monarchy (Mohammad Reza Shah) was replaced with another authoritarian Islamic Republic of Iran. The Arya Mehr University of Technology was seized by the Islamic fundamentalist and name of the Arya Mehr University of Technology was changed to Sharif University of Technology. From 1978 to 1987, the academic universities in Iran were closed for so-called "cultural revolution".

In 1980 Dr. Azam Niroomand-Rad and her family returned to USA. She then applied for National Institute of Health (NIH) Fellowship that enabled her to join the Department of Medical Physics at the University of Wisconsin in Madison, Wisconsin. Azam was the last Postdoc of Prof John Cameron. Azam worked under supervision of late Prof John Cameron and late Prof Herb Attix. She specialized in therapeutic medical physics. A couple years later, Azam became a member of AAPM and IOMP. Azam is certified by the American College of Radiology (ACR) in therapeutic medical physics (1988) and by the American Board of Medical Physics (ABMP) in Radiation Oncology Physics (1990).

From (1983-1988) Dr Niroomand-Rad worked as Assistant and Associate Professor at the Medical College of Wisconsin in Milwaukee, Wisconsin. In 1988, she moved to Washington D.C. and worked as Professor and Clinical Director of Medical Physics Section at the Department of Radiation Medicine at Georgetown University Medical School until her retirement in 2010. After retirement she returned to Madison, Wisconsin where she is continuing her research as an Honorary Professor at the Department of Medical Physics, University of Wisconsin in Madison, Wisconsin.

Prof Azam Niroomand-Rad has served on many AAPM committees and Task Groups including Chair of Radiation Therapy Working Group (1985), Organizer of Scientific Meetings at North Central and Midwest Chapters of AAPM, member of the AAPM Board of Directors (1986-1989) and (1997-2000), Finance Committee (1988-1991), International Affairs Committee (1988-1991), Ethics Committee (1988-1991), Chair of Task Group 1 to develop courses for developing courtiers (1990-1991), Chair of Developing Countries Committee (1989-1991), member of Radiation Protection Committee (1989-1996), Member of Task Group No. 46, Accelerator Beam Data (1989-2000), member of Radiation Therapy Committee (1992-1994), member of Local Arrangement Committee (1992-1993), Chair of Task Group 55 1993-1997) for radiochromic dosimetry, Chair of Education Committee of Mid-Atlantic Chapter (1994-2000), President of Mid-Atlantic Chapter (1996-1997), member of Awards and Honors Committee (1996-2001), Appointed Delegate to IOMP (1996-2000), ABMP Oral Examiner (1997), ABR Oral Examiner (1996, 1998, 2000, 2002, 2004, 2006), Chair Presidential Ad Hoc Committee, Women issues (1996-1997), Chair Task Group 8 Women in AAPM (1997-1999), Organizer of Symposium on Women in AAPM (1998), Course Director, Nashville, TN (1999), member of Long-Term Planning Committee (2000-2004), member of Science Council (2000-2004), Associate Editor of Medical Physics Journal (2001-2005), member of Education Council (2000-20006), member of History Committee (2007-2013), and Chair of Task Group 235 an update to radiochromic dosimetry (2012-2020).

Prof Azam Niroomand-Rad has served on many IOMP committees including member of Education and Training Committee (1991-1997), working with International Labor Organization (ILO) (1991- 2008) to establish Medical Physics profession in the listing of the International Standard Classification of Occupations (ISCO-2008), Chair of Education and Training Committee (1997-2000), Co-Chair of Advisory Committee for World Congress Planning Committee, in Chicago (1996-2000), Elected Vice President (2000-2003), President (2003-2006), Past

President (2006-2009), Awards and Honors Committee (1998-2000), member of IAEA (International Atomic Energy Agency) Scientific Committee (2001-2002), Organized First US-Cuba International Conference in Medical Physics in Havana, Cuba (2000-2002), an IAEA Expert, Radiation Therapy Physics, Jordan (2003), member of Program Committee of Poland Society of Medical Physics (2005), Chair History Subcommittee (2008-2019), co-organized Middle East First International Conference of Medical Physics in Shiraz, Iran (2011), and International Union for Physical and Engineering Sciences in Medicine (IUPESM) International Advisory Committee, World Congress, Toronto, Canada (2015).

Prof Azam Niroomand-Rad was Editor of IOMP Medical Physics World (MPW) Bulletin (1994-2000), Managing Editor and member of Electronic MPW (1996-2000), Azam was elected as IOMP first female Vice President in Chicago and (thus far the only) female medical physicists to serve as President (2003-2006) and Past President (2006-2009). She worked with ILO (International Labor Organization) for recognition and inclusion of Medical Physicists in the International Standard Classification of Occupations (ISCO-2008) that helped to open many doors to women medical physicists (WMPs) in health professional and health services.

Prof. Azam Niroomand-Rad is founder of the AAPM / IOMP International Scientific Exchange Programs (ISEP) Courses and Workshops in 1989. She has served as Chair of ISEP (1989-2006) and has helped to expand and advance medical physics organizations and associations in several developing countries including (but not limited to) Tehran, Iran (1991), Islamabad, Pakistan (1992), Baghdad, Iraq (2010), Rabat, Morocco (1996), Cairo, Egypt (1998), Moscow, Russia (1997), Istanbul, Turkey (1995), Bangkok, Thailand (2000), Dhaka, Bangladesh (2001), Riyadh, Saudi Arabia (2002), Manila, Philippines (2005), Yaoundé, Cameroon (2005), Nairobi, Kenya (2005), Chengdu, China (2004), Program Committee Nuremberg, Germany (2005), and Manama, Bahrain (2007).

Dr Azam Niroomand-Rad was as active member of electronic encyclopedia e-Encyclopedia of Medical Physics and Multilingual Dictionary of Terms, (EMITEL), and has coordinated scientific dictionary for Persian translation of EMITEL**.** She has published many articles, several Books, Book Chapters, and article describing Role and Responsibilities of Medical Physicists in Radiological Protection of Patients for IAEA.

Dr Azam Niroomand-Rad has been thesis advisor and co-advisor of three PhD students and eight MS students. She was Co-Inventor of couple patents with one patent registered at the US patent Office in December 2008. She has received many honors and awards including Honorary Doctor of Science Degree (DSc.) from Regent of the University of the State of NY (2001), Teacher of the Year Award, from Association of Residents in Radiation Oncology (2001), AAPM Life-Time Achievement in Medical Physics (Quimby Award) (2006), IOMP Marie Skłodowska Curie Award (2009). She is Fellow of AAPM (1997), Fellow of IOMP (2013) and Fellow of IUPESM (International Union for Physical and Engineering Sciences in Medicine (2022). Azam scientific and professional video interviews as conducted by late Prof. John Cameron (2004) and as conducted by Prof. Colin Orton (2021) as well as her biography are available at the AAPM History & Heritage video archives [52,53, 54, 55].

4. Pioneer Women Medical Physicists in the IOMP Regional Organization in Europe (EFOMP Region - Established in 1980)

In 2021 Medical Physics International (MPI) Journal published series of articles focused on the development of Medical Physics in EFOMP Regions [56, 57]. In addition, several MPI were published describing EMITEL/ EMERALD programs [58, 59, 73] as well as ICTP programs in Trieste, Italy [62, 73].

As per a survey in 2014 [79] the median value of female medical physicists in Europe is 47% of the professional workforce. As per data from 2015 [80] all medical physicists in the EFOMP Region were c.8400.

4.1 Edith Anne Stoney (1869-1938): First Woman Medical Physicist in Europe

Dr Edith Anne Stoney was born in 1869 in Dublin, Ireland. Her father was a well-known physicist. Edith graduated from Newnham College, Cambridge, Britain, but was not awarded a degree in 1893 as at that time women were excluded from graduation. However, later she was awarded BA and MA degrees from the Trinity College in Dublin, after they accepted women in 1904.

In 1874 London School of Medicine for Women was established that was the first medical school for women in Britain. In 1899 Edith Stoney started to work in this School as physics lecturer, thus becoming the first woman in the world to be employed in the field of medical physics. At that time medical students in Britain were taught by top physicists (such as J. J. Thompson in Cambridge). In 1901, the British Royal Free Hospital employed Edith and her sister Florence. The two sisters were in charge of selecting, purchasing, and installing x-ray equipment. During WWI Edith Stoney was trained to operate x-ray units.

During WWI, Edith Stoney established stereoscopy to localize bullets and shrapnel and introduced the use of X-rays in the diagnosis of gas gangrene. After the war Edith Stoney took a post as lecturer in physics at the King's College for Women. In 1936, Edith and Florence established Stoney Studentship in the British Federation for University of Women (BFUW) for research in biological, geological, meteorological, and radiological sciences. The Stoney studentship is now being administered by the Newnham College in Cambridge and supports clinical medical students going abroad for their elective period. Edith Stoney died in 1938 at age 69. [61]

4.2 Andrée Dutreix – Pioneer Woman French Medical Physicist

Andrée Dutreix studied math, physics and electronics at Sorbonne in Paris. She devoted her attention to the physical problems in medicine. She worked at the Institute of Gustave-Roussy, Villejuive, France. She developed standards for quality assurance in brachytherapy and tele-radiotherapy.

In 1949, nuclear medicine was a booming field. In 1950, Frédéric Joliot, then France's High Commissioner for Atomic Energy, decided to acquire a Betatron particle accelerator for nuclear experiments. To share the cost of the accelerator, he set up a team at the Institute Gustave Roussy (IGR). By 1953, the Betatron was to treat patients in the morning and to run physics experiments in the afternoon. Physicists did not want to work in a medical environment, for fear of not getting opportunities to do any scientific work. Andrée Dutreix took on the challenge and joined the team.

Andrée Dutreix was good in math and drawings. She calculated treatment dose distributions for Betatron. She made manual calculations prior to use of basic computers. Andrée Dutreix wrote Fortran code and calculated brachytherapy-treatment doses on an IBM computer.

Prof Andrée Dutreix made great contributions to the field of radiotherapy. Among her achievements, she improved the sparing of healthy tissue, changed the practice from kilovolt to megavolt treatments. She worked to obtain recognition for the medical physicists who worked with her. She created the first medical physics diploma in France in 1970. She managed the radiation Hospital in Villejuif, France for many years and later became a teacher at Louvain University.

Prof Andrée Dutreix became a corresponding member of the German Roentgen Society in 1979 and was awarded the Roentgen Plague in 1986. She also received IOMP Maria Skłodowska-Curie Award at World Congress 2003 in Sydney, Australia. On July 2009, Prof Andrée Dutreix was interviewed by Prof Azam Niroomand-Rad in her home in Paris on behalf of IOMP. The video interview is available at IOMP History Committee Archive. [63, 64, 65]

4.3 Roberta Breschi: First Woman Medical Physicist in Italy

Roberta Breschi was born in Prato, Italy. In 1961 she defended her doctorate in health physics at the Rome University "La Sapienza". Dr Roberta Breschi started her career as medical physicist (Radiotherapy) in the San Camillo Hospital, Rome, Italy.

In 1971 Dr Roberta Breschi became Director of the "Autonomous Health Physics Service" of the Pio Istituto di Santo Spirito in Rome. Dr Roberta Breschi had a wide profile of sub-specialties in medical physics. She was member of the Ministry of Health Commissions and Expert in medical physics and Qualified Expert Grade II for radiation protection.

Dr. Roberta Breschi also lectured medical physics for health professions at Lazio Regional and University Schools in Rome. She was member of the Board of Arbitrators of AIFM and AIRP (the Italian Associations in Medical Physics and in Radiation Protection). After her retirement, Roberta Breschi loved to deepen her culture on "Medical Physics", considering it a "Science for life" to evaluate the risk-benefit relationship in research, technological development, and healthcare.

4.4 Maria Stefanova (1922-1985): First Woman Medical Physicist in Bulgaria

Maria Grozdanova-Stefanova was born in Bulgaria in 1922. She was the first woman medical physicist in the country who in 1946 graduated in physics from Sofia University, in Bulgaria. She was then employed as lecturer in medical physics in the new Department of Medical Physics at the Medical Faculty of Plovdiv University, Bulgaria that was established in 1945. As part of her research, Maria made some of the first environmental radiation measurements in the country.

Dr. Maria Stefanova worked at the Medical University Plovdiv until her retirement. She authored several textbooks on medical physics in Bulgaria. Her daughter, Dr Vassilka Tabakova, also became a medical physicist and in 2020 published the first book on e-Learning in Medical Physics. She also took active part in the EMITEL Encyclopedia of Medical Physics. She worked along with her husband Slavik Tabakov in developing e-learning international materials EMERALD and EMIT - projects that received the EU Leonardo Da Vinci Award. [59, 60]

4.5 Barbara Gwiazdowska (1927-2014): First Woman Medical Physicist in Poland

Barbara Gwiazdowska was born in Warsaw, Poland in 1927. Prof. Barbara Gwiazdowska was the first woman working as medical physicist in Poland. She studied at the Faculty of Electrical Engineering of the Lodz University of Technology in Lodz, Poland. She then moved to Warsaw and studied at the Department of Physics of the Institute of Oncology Warsaw University of Technology. Under leadership of the department head, Dr Cezary Pawłowski, she was able to receive her PhD in the field of medical electrical engineering.

In 1952, Dr Barbara Gwiazdowska defended her diploma thesis and started working at the Department of Physics of The Maria Skłodowska-Curie Institute — Oncology Center Radium Institute in Warsaw. The Radium Institute was established in 1932 with support of Marie Curie's sister, Dr Bronisława Dłuska who put great efforts for the establishment of the Radium Institute in Poland. From 1965, Prof Dr Barbara Gwiazdowska was active in establishing the Polish Society of Medical Physics in Poland.

Dr Barbara Gwiazdowska served as national consultant in the field of medical physics in Poland. In 1972 she became Head of the Department of Medical Physics and at the same time, she was active in creating the specialty of medical physics at the Faculty of Physics of the University of Warsaw. Her activities were successful and her first student defended thesis in 1974.

Under the supervision of Prof. Barbara Gwiazdowska, a professional measurement laboratory was established, which was transformed into the Laboratory of Secondary Dosimetric Standards and became integrated into the international network under the auspices of IAEA.

In 1985, Prof Barbara Gwiazdowska received the highest university degree, Dr. habil and in 1996 the title of professor. From 2004 she was the National Consultant for Medical Physics. For many years, she simultaneously worked at the Oncology Center in Warsaw.

In 2013, Prof Barbara Gwiazdowska invited Professor Azam Niroomand-Rad to Krakow, Poland for the inauguration of First International Day of Medical Physics (IDMP) that had been established on 7 November – the birthday of Maria Skłodowska-Curie. As IOMP Past President, Azam made several presentations and reviewed Marie Skłodowska-Curie (1867-1934): A Scientist Ahead of her Time – Historical Overview, Tribute and her Contributions to Physics, Medicine, and Cancer Treatment. Moreover, Prof Barbara Gwiazdowska invited Azam to Warsaw to visit Marie Curie birthplace and Museum. [57]

4.6 Inger-Lena Lamm: Swedish Medical Physicist, First Woman President of EFOMP

Inger-Lena Lamm was born in Sweden. She studied at the Lund University, Faculty of Engineering in Sweden. In 1965, she graduated with a Master of Science in Engineering, Engineering Physics. She was teacher and researcher at the department of mathematical physics (1964-1974). She received her PhD in "Theoretical studies of some equilibrium properties of stably deformed nuclei" in 1974.

In 1974 Dr Inger-Lena Lamm changed her studies from mathematical physics to radiation physics – to use physics to the benefit of diagnosis and treatment of patients – formally completing her MSc in Medical Physics in 1976.

Dr Inger-Lena Lamm worked as medical physicist at the Lund University Hospital and she was engaged in clinical radiotherapy, education, training, and research from 1974 until her official retirement in 2011. With her broad background in mathematics, she was the physicist selected to introduce CT in radiotherapy treatment planning in 1977. During the last 20 years Dr. Inger-Lena Lamm was responsible for all brachytherapy activities. She developed and introduced new high-dose-rate (HDR) and low-dose-rate (LDR) treatment techniques.

Dr Inger-Lena Lamm was very active in promoting the Medical Physics Profession, especially in the harmonization of education and training standards. She was instrumental in the development of Medical Physics as a regulated health care profession in Sweden (1999). She was President of the Swedish Hospital Physicists Association (SHPA) (1987-1997) and Vice President of the Swedish Association of Scientists (1994-2006).

Dr Inger-Lena Lamm was Chairman of the Education, Training and Professional (ETP) Committee of the EFOMP (1995-1999), and she became the first woman President of EFOMP (2000-2002). Among many other activities, Dr. Inger-Lena Lamm participated in the development of several Policy Statements and in the establishment of the European School of Medical Physics, ESMP in 1998.

Dr Inger-Lena Lamm was also a member of IUPESM and Administrative Council (the first woman elected at this position). She was in several advisory committees. She held Board member positions in national and international organizations. She participated in EU projects and in the organization of national and international conferences and workshops. She took active roles in e-learning International EU projects, European MEdical RAdiation Learning Development (EMERALD) and European Medical Imaging Technology Training (EMIT). The team was awarded with the EU Leonardo Da Vinci Award in 2004.

Dr Inger-Lena Lamm continued as a member of the EMITEL Encyclopedia of Medical Physics team and coordinated the Swedish translation of the Scientific Dictionary of Medical Physics Terms (www.emitel2.eu). She was also involved in IAEA projects, among other things as lecturer in brachytherapy on regional training courses in Tunis in 1997 and in Cairo in 1999.

Since 1997 Dr Inger-Lena Lamm has been involved in radiation therapy standardization as an expert of International Electrotechnical Commission (IEC) subcommittee 62C, and she has been chairman of the Swedish mirror committee SEK TK62BC since 2005. She has received many awards including an Honorary member of EFOMP. She received the IEC Award in 1996. She became IUPESM Fellow (2022). [57, 58, 59, 73]

4.7 Anna Benini: First Woman (inaugural) Secretary- General of EFOMP

Anna Benini was born in Italy. She worked at the University of Parma and then moved to the IAEA. In 1988 Dr Anna Benini and Prof L. Bertocchi established the ICTP College on Medical Physics, dedicated to MP education for stidents from Low and Middle Income countries. ICTP - the Abdus Salam International Center for Theoretical Physics was founded in 1964 in Trieste, Italy by the Nobel Laureate Prof Abdus Salam. Dr Anna Benini was Co-Director of the College until she retired in 2018.

In 1980 Dr Anna Benini was elected the the inaugural Secretary-General of EFOMP – the first woman at this position. Later she took active role in the EMERALD project developing MP e-learning materials. Dr Anna Benini was elected as inaugural member of Education and Training Committee (ETC) of IOMP (1985-89) and was member of IOMP Professional Relation Committee (PRC) during (1994-1997). She was awarded with the ICTP Outstanding Role Diploma. Currently Dr. Anna Benini is retired and lives in Denmark. [57, 58, 62, 73]

5. Pioneer Women Medical Physicists in the IOMP Regional Organization in Latin America (ALFIM Region – Established in 1984)

In 2018 and 2019 Medical Physics International (MPI) Journal published several articles focused on the development of Medical Physics in Latin America. [66, 67]

As per a survey in 2014 [79] the median value of female medical physicists in Latin America is 24% of the professional workforce. As per data from 2015 [80] all medical physicists in the ALFIM Region were c.800.

5.1 Esther Nunes Pereira: (1916-2003) Pioneer Woman Medical Physicist from Brazil

Esther Nunes Pereira was born in the Federal District, (today the city of Rio de Janeiro), Brazil in 1916. She received her Bachelor of Science Degree in physics and mathematics from the Faculty of Philosophy at the University of Brazil In 1944. She was encouraged and influenced by Dr Osolando Machado, radiotherapist, to become interested in ionizing radiation.

In 1954, Esther was hired by the National Cancer Institute (INCA) in Rio de Janeiro for activities related to physics as applied to medicine in the sections of Roentgentherapy, Curietherapy and Radioisotopes at INCA. Esther took courses at the National Institute of Technology on Electric and Electronic Measurements (1952-1954), Radioisotope Methodology and Radiological Dosimetry at the University of San Paulo (USP).

From 1953 to 1958 Esther worked at the Nuclear Dosimetry and Instrumentation at CNEN in Brazil. On April 1960, with a scholarship from IAEA, Esther went to the Christie Hospital and Holt Radium Institute, in Manchester, UK, where she interned for one year until May 1961 under the supervision of Dr Meredith. She also took a course on Radioisotopes at the Isotope School in Wantage, UK.

From 1972 to 1973 Dr Esther Nunes Pereira assumed the leadership of the Sector of Agreements, Covenants and Autarchy of the National Division of Cancer. She became the Head of the Radiation Physics Sector at INCA, which at that time belonged to the National Cancer Division. After a lifetime dedication to the physics of ionizing radiation at INCA, she retired in1986. She passed away in 2003. [67]

5.2 Simone Kodlulovich Renha: Eminent Woman Medical Physicist from Brazil, twice President of ALFIM (2010-2013) and (2013-2016)

Simone Kodlulovich Renha was born in Brazil. She obtained her PhD in Nuclear Technology with specialization in medical physics at Instituto de Pesquisas Energéticas e Nucleares in Brazil.

Since 1999 Simone Kodlulovich Renha worked as a researcher at the National Commission of Nuclear Energy (CNEN). For more than 10 years she was Head of Diagnostic Radiology Division of the *"Instituto de Radioproteção e Dosimetria"* (IRD/CNEN).

Since 2001 Dr Simone Kodlulovich Renha became a professor of the postgraduate program of IRD/CNEN where she supervised students' research mainly in diagnostic radiology and in radiation protection and safety in medical applications of ionizing radiation. Later she served as an IAEA expert and at present she serves as Coordinator of the IAEA project "Enhancing Capacity Building of Medical Physicists to Improve quality and safety in medical practices" for Latin America

From 2010 to 2013 Dr Simone Kodlulovich Renha served as President of "*Asociación Latinoamericana de Física Médica* (ALFIM). She was re-elected for the period (2013-2016) and of the *Radioprotection Federation of Latin America and the Caribbean* for the period (2018-2021). The first woman ALFIM President was the medical physicist from Venezuela Dr Lila Carrizales (1998-2001).

In IOMP, Dr Simone Kodlulovich Renha was a member of the Education and Training Committee and Chair of the Honors and Awards Committee (2015-2018, 2018-2022). Currently she works as a member elected of the International Medical Physics Certification Board and as chair of IOMP Professional Relation Committee (PRC). She is Fellow of IOMP (2017) and a Fellow of IUPESM (2022). [67, 73]

5.3 Clemencia García Villasmil: (1925-2000) First Woman Medical Physicist in Venezuela

Clemencia Garcia Villasmil was born in Caracas, Venezuela in 1925. She was a renowned Venezuelan and pioneer scientist who was specialized in Radiological Physics. Clemencia went to Europe when her father was consul of Venezuela in Geneva Switzerland. Clemencia studied at the Ecole Burchbül in Geneva. At the start of WWII, the family returned to Venezuela and Clemencia obtained a Bachelor of Science degree in physics and mathematics at the University of Fermín Toro in Caracas, Venezuela. Then she continued her education at the Pedagogical Institute in Venezuela. Later she went to Cuba and continued her studies at the University of Havana, Cuba.

Clemencia Garcia Villasmil then moved from Cuba to Columbia University. Clemencia was the only woman among 129 students in class of 1953. She stood out as the only woman obtaining the degrees of BSc in Physics and Doctorate in Radiological Physics. In the university there were two other Venezuelans Dr Raúl Vera Vera, distinguished Physician Radiotherapist of recognized trajectory and Dr Marcel Roche, first Director of Central University of Venezuela, International Atomic Energy (IVIC).

Dr Clemencia Garcia Villasmil was founder of Henry Becquerel Laboratory, the Radiation Physics area of the Cancer Hospital Luis Razetti in Quote, San José Parish, Caracas, Venezuela, from the José María Hospital Vargas, La Guaira, Venezuela and the Central Hospital of the Armed Forces, now Military Hospital Dr. Carlos Arvelo. In 1953, by founding the Henry Becquerel Laboratory, Clemencia became a pioneer in the provision of personal dosimetry services in Venezuela. She made treatment calculations, teaching physician specialists, and calibration of the radiotherapy units that at that time there were about thirty units throughout Venezuela.

Dr Clemencia Garcia Villasmil worked with her own equipment and calibrated them at the US National Bureau of Standards in Washington D.C., USA when the country still did not have a laboratory for dosimetric calibration.

In 1960s, Dr Clemencia Garcia Villasmil received an honorable mention from the Atomic Energy for her research work with the Cobalt units that was manufactured by Canada. Dr Clemencia Garcia Villasmil demonstrated a design failure of the Cobalt units by and presented a radiation leak that she was able to verify at the Luis Razetti Cancer Hospital which helped the manufacturer to redesign the equipment.

Dr Clemencia Garcia Villasmil directed the Radiation Physics section of the Domingo Luciani Hospital and the University Hospital in Caracas, Venezuela. At that time, she was the only non-medical teacher at UCV Hospital. She participated in various Scientific Societies. Being a founding member of the Venezuelan Society of Oncology, associate member of the Venezuelan Society of Radiology, she received many awards and honorary distinctions. Dr Clemencia Garcia Villasmil died in 2000 while she was teaching at the Hospital Universitario de la UCV. [67]

5.4 Patricia Mora: First Woman Medical Physicist in Costa Rica, ALFIM President (2022-2025)

Patricia Mora was born in Costa Rica and since her high school year´s she loved physics and medicine. She graduated from the University of Costa Rica (UCR) with a Bachelor of Science degree in physics. In 1986, Patricia Mora obtained her Master of Science in Medical Physics from the University of Wisconsin-Madison, USA. Upon her return to Costa Rica, she joined the School of Physics at UCR, where she began teaching undergraduate physics courses.

Up until Patricia retirement (December 2018), she worked for more than 35 years at the UCR, where she was able to initiate and consolidate large-scale programs such as the Radiological Safety Plan, the first personal dosimetry laboratory in the country and the only radiation metrology laboratory in the country (now seeking to become a SSDL).

In 2010, Patricia Mora was co-founder the academic master´s degree in medical physics at the UCR. During the period 1996 to 2018, she was a member of the Board of Directors of the Costa Rican Atomic Energy Commission where she was President for several periods. From there, she channeled and promoted IAEA technical cooperation in Costa Rica.

Patricia Mora worked on IAEA projects on issues of patient radiation protection, optimization, and quality assurance programs in mammography. Patricia Mora co-authored several IAEA books about mammography Quality Control (QC) programs. She has recently contributed to the new IAEA methodology for remote and automated QC in general diagnostic radiology and mammography. In 2019, Patricia was appointed Secretary General of the ALFIM and at is now serving as President of ALFIM (2022-2025). [67]

6.0 Pioneer Women Medical Physicists in the IOMP Regional Organizations in Asia and Oceania Region (AFOMP: Established 2000) and South-East Asia (SEAFOMP: Established 2000)

The MPI published a series of articles for these Regions. [68, 69, 70, 71, 72, 74]

As per a survey in 2014 [79] the median value of female medical physicists in Asia (AFOMP+SEAFOMP) is 35% of the professional workforce. As per data from 2015 [80] all medical physicists in AFOMP+SEAFOMP Region were c.5100.

6.1 Anchali Krisanachinda: Founding Member of Medical Physics in Thailand and First Woman President of SEAFOMP

In 1967, Anchali Krisanachinda graduated in physics from the Chulalongkorn University in Bangkok, Thailand. In 1971, she obtained her MSc in Medical Physics from the University of London, UK. In 1997, she completed her PhD from the Chicago Medical School, USA.

In 1968, Dr Anchali Krisanachinda started her career at the Ramathibodi Hospital Mahidol University, in Bangkok. From 1978 to 1981 she was Director at the School of Medical Physics at Mahidol University that had been established in Thailand (1944). Later Dr Anchali Krisanachinda worked at the Chulalongkorn University in Bangkok, where she became Professor and Head of Nuclear Medicine in 2003.

Prof Anchali Krisanachinda is founding member of the Medical Physics Club of Thailand. She has been deeply involved in promoting the development of medical physics in Asia, particularly in South-East regions. She was one of the Founding Officers of AFOMP and SEAFOMP. In 2000 she was elected AFOMP Treasurer and in 2001 she was elected SEAFOMP Vice President and served as President from 2005.

In 2000, under leadership of Prof Anchali Krisanachinda, Thailand hosted the first AFOMP Congress in Bangkok in conjunction with the IOMP/AAPM ISEP Courses/workshops. She also organized the first AOCMP Congress in conjunction with the 2nd SEACOMP in Bangkok. She also organized the 7th SEACOMP in Chiang Mai, the largest city in northern Thailand. In 2016, she also Co-organized and Co-chaired the 22nd IOMP International Conference of Medical Physics (ICMP) in Bangkok.

Prof Krisanachinda, in her own personal capacity as well as her official capacity of AFOMP and SEAFOMP, has helped medical physicists in Brunei, Cambodia, Laos, Myanmar and Vietnam to establish their own national medical physics organizations. She contributed to the development of MP profession in these countries.

Prof Krisanachinda has been serving as IAEA National Project Coordinator for Thailand under the Regional Cooperative Agreement (RCA) for the Asian Region (RAS) and has completed several projects since 1985. The projects included IAEA programs in Quality Assurance (QA) and QC, DAT and DATOL (Distance Assisted Training Online) in nuclear medicine. She has strengthened MP through Education and Training in Asia and Pacific where a structured clinical training program for medical physicists was initiated in Thailand. This was an IAEA residency training program (initially started as a pilot program in 2007 and now is a regular one) for medical physicists practicing in diagnostic radiology medical physics, radiation oncology medical physics and nuclear medicine in Thailand under Thai Medical Physicist Society and Chualalongkorn University in Thailand.

In 2005, Prof Krisanachinda was appointed as IAEA expert and consultant in the field of nuclear medicine and medical physics and took IAEA missions to several South-East Asian countries. In recognition of Prof. Krisanachinda achievements in global development of MP and her outstanding contributions to the services and activities of IOMP, AFOMP, SEACOMP and the IAEA, she was awarded the IOMP Harold Johns Medal (2018), Fellow of IOMP (2013) and of Fellow of IUPESM (2022). [69, 70, 71, 72, 73]

6.2 Agnette Peralta: Founding President of the Philippine Organization of Medical Physicists (Society of Medical Physicists, Republic of the Philippine)

Agnette Peralta, was born in Manila, Philippine. She received the Master of Science in Applied Physics (Medical Physics) Program from the University of Santo Tomas Graduate School which is the oldest and largest Catholic School in Manila, Philippine. Since 1983, she has been a faculty member at this University - the only university in the country that offers the medical physics program in the Philippines. She completed her Bachelor of Science (Physics) degree from the University of the Philippines.

Agnette Peralta received her Master of Science in Medical Physics from the University of Wisconsin – Madison, USA. She is the Founding President of the Philippine Organization of Medical Physicists, now known as the Society of Medical Physicists in the Republic of the Philippines. She was also the President of the South-East Asian Federation of Organizations for Medical Physics (SEAFOMP) from 2010 to 2012.

From 1991 to 2016 Dr Agnette Peralta served as Director of the Radiation Health Service which later became the Center for Device Regulation, Radiation Health, and Research of the Food and Drug Administration. In 2005

Dr Agnette Peralta organized the IOMP/AAPM ISEP Courses and Workshops. She retired from the Department of Health as an Assistant Secretary of Health in October 2017 and was named one of the outstanding medical physicists in the Asia-Pacific region. [69, 70, 72, 73, 74]

6.3 Djarwani S. Soejoko (1945), Founder of Medical Physics in Indonesia

Djarwani Soejoko was born in Salatiga, Indonesia in 1945. She received her Bachelor of Science and Master of Science degrees from the University of Indonesia in the field of physics of materials. She obtained her PhD in the field of biophysics from the Bandung Institute of Technology (ITB), that was established in 1920. Dr Djarwani Soejoko dissertation was titled "A study on the composition and structure of mineral compounds in the cuticle of macro brachium rosenbergii and penaeus monodon and their evolutions during the moulting period".

Prof Djarwani Soejoko is one of the few senior scientists in the Department of Physics at the University of Indonesia. She is still active in research and teaching as well as tutoring the students in medical physics. She has published several articles in the national and international journals. She is the founder of the Medical Physics in Physics Section of the Department of Physics. For her services and dedication, she has been awarded with the "Satya Lencana Karya 30 Years". [68, 69, 70, 72, 73, 74].

6.4 Kanae Nishizawa and Keiko Imamura: Eminent Woman Medical Physicists in Japan

Dr Kanae Nishizawa is an eminent medical physicist who graduated from Tokyo University of Science in 1973. From 1973 to 1991 she was medical physicist in Kyorin University of Medicine, Department of Radiology and from 1991 to 2010 she was working at the National Institute of Radiological Sciences, Japan. Her specialty is radiation protection and dosimetry. She has published many articles in Japanese and English. She took an active part in Japanese translation of the Scientific Dictionary of Medical Physics (www.emitel2.eu).

Dr Keiko Imamura is also an eminent medical physicist. She graduated in 1969 the Ochanomizu University and defended her doctorate in 1974 at University of Tokyo, Japan. From 1974 to 2007 she was medical physicist in St. Marianna University Hospital, Department of Radiology. Her specialty is Physics of Diagnostic Radiology and Magnetic Resonance Imaging (MRI). She has published many articles in Japanese and English. She also took active part in the Japanese translation of the Scientific Dictionary of Medical Physics (emitel2.eu). [58, 71, 74]

6.5 P.N. Manorani Vijayam – Eminent Woman Medical Physicist in India

Dr P. N. Manorani Vijayam is one of the first women medical physicists in India, who started her career in 1960s (also in the 1960's started her careers Sharada K.S. and Reshamwala H.H.). Dr Vijayam completed the Diploma in Radiological Physics (DipRP) from Bhabha Atomic Research Centre (BARC), Mumbai in 1967. She joined the Radiation Standards Section of BARC in late 1968 and continued working there for 33 years, until 2002. She was associated with development of ionometric standards for Co-60 teletherapy beams which was used by BARC for a long time. She was also associated with conducting the dosimetry audit in beam therapy. In addition, she was involved in calibration of radiotherapy dosimeters of the hospitals. Dr. Vijayam was also involved in teaching and training of DipRP students and trainees. [71, 73]

6.6 Parvaneh Shokrani (1959): Frist Woman Medical Physicist from Iran

Prof Parvaneh Shokrani was born in Isfahan, Iran in 1959. She completed her high school education in 1980, majoring in mathematics. She then completed her undergraduate physics education at University of Isfahan, in Isfahan, Iran in 1985. She then went to University of Cincinnati in Ohio and completed her MS degree in health physics and radiation protection in 1988. Later, she completed her PhD in medical physics, specializing in physics of radiation therapy from University of Cincinnati in 1992. Her PhD research thesis was "Application of Monte Carlo Simulation of Total Skin Electron Therapy for Treatment Optimization".

Prof Parvaneh Shokrani taught medical physics and did research for many years at Isfahan University in Iran. She has been author and co-author of 55 peer-reviewed scientific articles. She has written couple books in portal design and imaging and radiation protection. In 2013, Dr Shokrani registered her patent in Iran on "*A novel treatment method for lip carcinoma using an internal dose enhancer tool*". Dr. Shokrani has received many honors and awards, including University-wide investigator of the year award Isfahan University of Medical Sciences, Isfahan, Iran (2013).

6.7 Eva Bezak from Australia, First Woman President of AFOMP

Prof Eva Bezak, FACPSEM, FIUPESM holds MSc in Medical Physics (University of Adelaide, 1994) and PhD in Nuclear Physics (Australian national University, 1998) and is an internationally known medical physicist and Professor in Medical Radiation at the University of South Australia (from 2015). Prior to 2015, she spent 17 years in industry as a medical physicist at the Royal Adelaide Hospital (RAH), becoming Chief in 2006. She was the first female president of the Australasian College of Physical Scientists and Engineers in Medicine (ACPSEM; 2010-2012), she secured $5.5M of government funding for an Australian medical physics training. In 2015 she was appointed to the Administrative Council of the International Union for Physical and Engineering Sciences in Medicine (IUPESM) and was founding member of the IUPESM Women in Medical Physics and Biomedical Engineering Task Group. In 2017 she became the first female Vice president (now President, 2023) of the Asia-Oceania Federation of Organizations for Medical Physics (AFOMP). In 2019 she was appointed the Secretary General of the International Organization for Medical Physics and was elected the IOMP Vice-President in 2022. She is a convenor for the IUPESM World Congress 2025, to be held in Adelaide, Australia.

Prof Eva Bezak is a co-author of the Australian Academy of Science Report on future accelerators in Australia (2016) informing the government on the need for proton therapy and a past member of the National Radiation Oncology Tripartite Committee that developed quality and performance standards for radiation oncology in 2012 directly impacting the quality and the delivery of radiation oncology services in Australia. She co-authored the Tripartite National Plan for Radiation Oncology 2012-2022 as well as the National Needs Analysis Survey, examining accessibility to antenatal ultrasound and training in rural Australia (2022). Additionally, she is author of over 200 publications and 3 books and has supervised over 40 research postgraduate students (MSc, PhD).

In 2019 she was included in the South Australian Women's Honour Roll, tributing South, Australian women who have made a significant impact on the community, women who are role models and leaders. [71, 73]

6.8 Hasin Anupama Azhari from Bangladesh – First Woman Secretary General of AFOMP

Prof Hasin Anupama Azhari was born in Bangladesh and awarded PhD in Medical Physics from National University in 2011 in collaboration with OWSD, ICTP, Trieste, Italy. Her research station was in Zhejiang Cancer Hospital, China and German Cancer Research Centre (DKFZ). She became the Chairman of Medical Physics and Biomedical Engineering Department, Gono University (GB) as well as Dean, Faculty of Physical and Mathematical Sciences, GU and made her efforts developing medical physics education there until 2021. Currently, she is serving as Director of the Centre for Biomedical Sciences and Engineering at the United International University (UIU), Dhaka, Bangladesh. She has academic experience more than 15 years in medical physics field.

Prof Hasin Anupama Azhari has published more than 50 research works in different national and international journals and books. She has participated and organized various workshops, training programmes, conferences in different countries. Prof. Azhari has been playing an important role in cancer screening and awareness programme and arranging of accredited training program for cancer professionals for the SA regions through the South Asia Centre for Medical Physics and Cancer Research (SCMPCR) under Alo Bhubon Trust. Prof Azhari is an Executive Member of OWSD (Asia and Pacific Region), Secretary-General of AFOMP (2019-2022) and Vice-President of AFOMP from 2022. She is the founder President and advisory member of Bangladesh Medical Physics Society (BMPS), Secretary General, Alo Bhubon Trust, Vice President, Bangladesh Association of Women Scientists (BAWS), Regular Associate, ICTP, Association of Medical Physicists of India (AMPI), Life-time Member, Bangladesh Physical Society (BPS), Member of ESTRO, AAPM.

Prof Hasin Anupama Azhari is the first woman Medical Physicist in Bangladesh with MSc in MP, she has communicated with the health ministry and other government, nongovernment organization to publicize of the subject. In her tenure in BMPS she assisted and worked with Directorate of Health Services and Ministry of Health to create GO and recruitment rules for medical physicists and till now trying the MP order for public hospital to be gazette.

Prof Hasin Anupama Azhari has received International Medical Physics Day Award, IOMP in 2018 and Outstanding Medical Physicists Award, AFOMP, 2020. She was a project coordinator for Bengal translation at EMITEL e-Encyclopaedia of Medical Physics and Multilingual Dictionary and terms. She also acts as a PD for the student teacher exchange program between Heidelberg University Germany and GU through DAAD scholarship for 8 years. [58, 71, 73]

7.0 Pioneer Women Medical Physicists in the IOMP Regional Organization in Middle East Region (MEFOMP – Established 2009):

The MPI published several articles focused on the development of Medical Physics in the Middle East Region. [75, 76]

As per a survey in 2014 [79] the median value of female medical physicists in the Middle East is 50% of the professional workforce. As per data from 2015 [80] all medical physicists in the MEFOMP Region were c.600.

7.1 Hanan Rima: First Woman Medical Physicist in Lebanon

In 1984 Dr Hanna Rima received her PhD in Radiological Medical Physics from University Paul Sabatier, France. Then Dr Hanna Rima worked as Chief Medical Physicist at the North Hospital Centre in Lebanon.

7.2 Huda Al Naemi: First Woman Medical Physicist in Qatar, First Woman President of MEFOMP (2018 – 2022)

Dr Huda Al Naemi, completed her PhD in Qatar in 1999. Dr Huda Al Naemi has served as the first Inaugural Secretary-General of MEFOMP. Since 2006, Dr Huda Al Naemi has served as the President of Qatar Medical Physics Society (QaMPS). She also served as the first President of MEFOMP (2018 – 2022). Dr Huda Al Naemi is the Executive Director of Occupational health and safety since 2006. Dr Huda Al Naemi has been an affiliated Assistant Professor in the Weill Cornell Medicine in Qatar since 2019.

Dr Huda Al Naemi has received the State Encouragement Award for Medical Sciences Category in 2017. Dr Huda Al Naemi has also received the Healthcare Gold Medal from the Institute of Physics and Engineering in Medicine (IPEM) in 2019.

7.3 Jamila Al-Suwaidi: First Woman Medical Physicist in United Arab Emirates

Dr Jamila Al Suwaidi received both MSc and PhD in radiation physics from the University of Surrey, UK. Dr Jamila Al Suwaidi was the first medical physicist in the United Arab Emirates and she became the first President of Emirati Medical Physics Society (2005-2009). She is the first Emirati specialist to obtain postgraduate qualifications in the field of medical physics. Dr Jamila Al Suwaidi received the UAE Presidential Award in Sciences in 2012.

7.4 Laila Al Balooshi: First Woman (inaugural) Secretary General of MEFOMP from United Arab Emirates

Ms Laila Al Balooshi from the United Arab Emirates is experienced medical physicist with a distinguished history of working in the hospital and healthcare industry. She is Head of Medical Physics Section, Dubai Hospital in Dubai Health Authority. Ms Laila Al Balooshi was the first Secretary-General of MEFOMP (2015-2018).

7.5 Shada Ramahi: First Woman Medical Physicist in Jordan

Dr Shada Ramahi is Jordanian medical physicist in radiation oncology. She is the first woman medical physicist in the region to be examiner in the International Medical Physics Certification Board (IMPCB) since 2019. She was working as Chief Medical Physicist in King Faisal Specialist Hospital & research Centre, Saudi Arabia. In March 2020, Dr Shada Ramahi moved to USA as clinical Associate Professor at the University of Pittsburgh, Pennsylvania, USA.

8. Pioneer Women Medical Physicists in the IOMP Regional Organization in Africa (FAMPO Region – Established in 2009)

The MPI has published several articles focused on the development of Medical Physics in the African Region (FAMPO). [77, 78]

As per a survey in 2014 [79] the median value of female medical physicists in Africa is 33% of the professional workforce. As per data from 2015 [80] all medical physicists in the FAMPO Region were c.400.

8.1 Boutayeb Salwa: Senior Woman Medical Physicist from Morocco

Boutayeb Salwa started her medical physics career in 1993. She completed her engineering degree from the National Institute of Nuclear Sciences and Techniques of Cadarache, in France, and her PhD from the Atomic Physics Center of Toulouse University, in France.

Dr Boutayeb Salwa is Senior Medical Physicist and is now serving as the Head of Medical Physics section at the National Oncology Institute of Rabat in Morocco. In addition, Dr Boutayeb Salwa provides Education and Training in Medical Radiation Physics for Moroccan and foreign medical physicists. She is an IAEA expert and has coordinated couple projects in African countries that are affiliated with FAMPO.

8.2 Nadia Khelassi-Toutaoui: First Woman Medical Physicist from Algeria

Nadia Khelassi-Toutaoui started her career in 1995 at the CRNA Centre in South Africa. In addition, she has involved in academic and has taught practical training courses to students. Dr Nadia Khelassi-Toutaoui is currently working at the School of Nuclear and Allied Sciences, University of Ghana in Ghana.

8.3 Zeinab Eltaher: Eminent Medical Physicist from Egypt

Dr Zeinab Eltaher graduated in 1977 from the Faculty of Science, Cairo University, Egypt. She started her work at National Cancer Institute, Cairo University in 1978 and gained her PhD. She was the first to apply the total skin treatment at the National Cancer Institute, Egypt. Dr Zeinab founded medical physics sections in various Egyptian Governorates. Her contributions to developing the quality of radiotherapy treatment in Egypt continue until now and she has many publications. Recently she led a team of distinguished physicists to establish a radiation oncology department with most recent technology.

8.4 Rebecca Nakatudde from Uganda: First Woman FAMPO Vice-President

Mrs Rebecca Nakatudde works as a Medical Physicist at the Makerere University, College of Health Sciences, in Uganda. She was the first African woman speaker at the IOMP Project on medical physics development in Africa (ICMP 2013, Brighton, UK).

9. CONCLUSION

Together with bios of the pioneer women scientists with special contribution to physics, which reflected in medical physics, the paper includes short bios of 36 pioneer women medical physicists from IOMP Regional Organisations in all continents (EFOMP, ALFIM, AFOMP, SEAFOMP, MEFOMP, FAMPO) and North America. The indicative samples/bios were chosen from various types of societies. The paper lists only some early women medical physicists per Regional Organisation (RO), leaving to each RO to create a full list of all pioneer women medical physicists from each IOMP National Member Organisation (NMO). Such future survey(s), combined with all first colleagues in each NMO, will form a very valuable record of the historic development of our profession, thus tracing vectors for development in the future global professional development and recognition of medical physics.

During the 60 years of its activities, IOMP helped many countries, especially in the Low-and-Middle Income Regions to start their medical physics activities, to organize educational courses and training programmes, to boost their contribution to the overall development of global healthcare. This history paper shows an important part of this progress, associated with the involvement of women in this contribution. The paper was planned to cover the period to 2018, while the new plans and activities of the IOMP Women Sub-Committee (WSC) will be presented in a separate paper, led by L Marcu, the current Chair of WSC.

The authors of the paper are from the IOMP History Sub-Committee (HSC) and have led the presentation of IOMP History over the years, plus the development and update of the IOMP History Tables, including the names of all colleagues contributing to IOMP activities during the past 60 years. A recent publication of the MPI Journal includes all these history articles [81].

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HISTORICAL VIGNETTES AND A CURRENT PERSPECTIVE ON WOMEN'S CONTRIBUTIONS TO BRACHYTHERAPY

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Abstract— Beyond Marie Curie, the historical account of the development of brachytherapy by men is well documented and recognized. Yet there have been tremendous contributions by women since the inception of brachytherapy, from both clinical and technical perspectives. This report provides vignettes of select women and captures the historical context for their contributions to the field.

Keywords— Brachytherapy, Women, Development, History.

1. INTRODUCTION

With the accidental discovery of radioactivity in 1896 by Henri Becquerel at the École Polytechnique in Paris, and the subsequent deep investigation of naturally occurring radioactive substances and minerals (later identified and labeled as radium and polonium) in 1898 by Pierre Curie and Maria Skłodowska-Curie at the École Municipale de Physique et de Chimie Industrielles (also in Paris), all three were awarded the Nobel Prize in Physics in 1903 [1]. Based on self-experimentation and before Becquerel's passing in 1908 (for unknown causes, possibly due to radiation poisoning) and Pierre Curie (being killed by a heavy horse-drawn cart) in 1906, they posited that the radioactive emanations could be used in medicine [2]. Pierre Curie suggested to a Parisian physician (Henri-Alexandre Danlos) that their radiochemical reductions could possibly provide therapeutic benefit [3]. Application of radionuclides for radiation therapy spread globally [4,5], in large part due to the continued investigations of Maria Skłodowska-Curie and her efforts to share these sources, expand production, and develop source calibration standards. As documented by Skowronek [6], she was the first woman in Europe to receive a natural science doctorate, the first female laboratory head, lecturer, and professor at the Sorbonne University in Paris, and the first person to be twice awarded the Nobel Prize (the 2nd was for Chemistry in 1911). All the while raising two daughters alone. Only then was she slowly recognized on the international stage of scientific leaders (Fig. 1). These are amazing accomplishments, especially considering the culture at the time when women were not accepted or taken seriously in scientific circles.

Following Marie Curie's extraordinary accomplishments and the birth of brachytherapy, this report focuses on a select group of women who have made substantial contributions early to the field of brachytherapy. Not all female contributors to the advancement of brachytherapy are included in this article, and those involved with conventional clinical or technical aspects are excluded. As a means of not excluding any contemporary individuals, only women who have passed are described in detail. Please also note that the authors are not professional historians who have obtained original materials for providing these historical vignettes. The original aspect to this report is the historical focus and modern perspective on women innovators in brachytherapy.

A

B

Fig. 1. (A) Marie Curie sits in concentration with fellow Parisian Henri Poincaré during the extended photographic exposure at the invitation-only Solvay Conference on Physics in 1911. Ernest Solvay (seated 3rd from left) was not in attendance, but was photoshopped into the official print. (B) Having attended every Conference since its inception, Curie is joined at the 7th Solvay Conference on Physics in 1933 for the first time with other women (seated in the first row), including her eldest daughter (Irène Joliot-Curie, a future Nobel Laureate) and Lise Meitner. The 8th Solvay Conference on Physics was held in 1948, after World War II and long after Curie died in 1934 due to radiation poisoning. Images taken from the public domain.

2. WOMAN INNOVATORS IN BRACHYTHERAPY

Margaret Cleaves grew up in rural Iowa and shadowed her physician father up until his death when she was 13 [7]. She earned a medical degree at age 25 in 1873 from the State University of Iowa. Cleaves' first position was at the Iowa State Hospital for the Insane. Here she spearheaded and spread awareness about the imperativeness of female physicians for female patients in order to offer care and correctly recognize and treat gynecological pathology. She later set up private practice where her mission was to promote regular pelvic exams to catch disease early since male physicians were reluctant to do this. The current culture was misguided and associated women's insanity with remotely presenting disease such as in the pelvis. Continuing her championing of women's healthcare, she brought attention to a neurological disorder (neurasthenia), which at the time was being diagnosed in overworked men (c.f., chronic fatigue syndrome) [8]. Cleaves recognized the prominence of overworking in women too and called attention for women to also be possibly diagnosed with neurasthenia. She traveled to New York and Paris to learn more about electrotherapy, and Aronowitz and colleagues posit that she sought familiarity with the new application of electricity to medically treat insane patients [8]. This application of electricity was termed *Franklinization* after Benjamin Franklin. In 1903 she learned of radium and acquired sources on loan from the University of North Carolina. The ^{226}Ra was contained inside a glass vial, which did not substantially attenuate the beta and low-energy radiation. Her first patient was a man with a painful sarcoma of the inner cheek that failed to respond to x-ray exposures. After two treatments with radium, the pain subsided and the therapy was considered a success. Her second patient was a woman with advanced squamous cell carcinoma of the cervix who failed prior treatment with UV light and internally-applied x-rays. Again, two treatments were given on subsequent days and the therapy was also considered a success. She then traveled to Atlantic City to present her findings at the American Electro-Therapeutic Association annual conference [9]. Cleaves appears to be the first globally to have used the newly created ^{226}Ra sources for intracavitary gynecologic brachytherapy, which remains the most frequently used application of brachytherapy [7].

Edith Quimby was born in 1891 and graduated from high school in Boise, Idaho. After completing a master's degree from the University of California, she moved to New York in 1919 to work as a medical physicist at Memorial Hospital with Gioacchino Failla, the medical physicist director. Having a woman work in this field was exceedingly rare, but they worked together for over forty years [10]. In 1941 she was appointed as assistant professor at Cornell University, was promoted to full professor in 1954, and retired in 1960. Quimby was awarded the Janeway Award by the American Radium Society in 1940, received the Gold Medal from the Radiological Society of North America in 1941, was elected president of the American Radium Society in 1954, received an honorary doctorate from Rutgers University in 1956, was awarded the Gold Medal from the American College of Radiology in 1963, received the William D. Coolidge Gold Medal from the American Association of Physicists in Medicine (AAPM) in 1977, and became the first female Gold Medalist from the American Society of Radiation Oncology (ASTRO) in 1978, one year after the award was established. Quimby died in 1982. In 1996, the AAPM transformed their Achievement in Medical Physics Award to the Edith H. Quimby Lifetime Achievement Award. Quimby made numerous contributions to the field of radiological physics, but is most known today for developing a simple algorithm for permitting accurate yet quick brachytherapy dose calculations that accounted for the patient-specific geometry of the implant. The method became known as the Memorial System, which provided uniform loading of source strength to produce inhomogeneous dose distributions [11, 12]. It contrasted with the method developed by Paterson and Parker at the Holt Radium Institute in Manchester which provided non-uniform loading of source strength to produce homogeneous dose distributions [13]. Her approach revolutionized and simplified the approach to brachytherapy dose calculations in the pre-computer era and harmonized clinical practice in the U.S. and beyond.

For further perspective on women's contributions in the prior century, the University of Chicago documents the tribulations and accomplishments of Anna Hamann as their first full-time radiation oncologist [14]. She studied under Wilhelm Röntgen despite his documented intolerance for female medical students, yet she successfully completed training and subsequently pursued research with Otto Hahn during his discovery of radioelements and subsequent awarding of the Nobel Prize in Chemistry (1944, denying recognition and contributions from Jewish physicist Lise Meitner) [15].

Frédéric Joliot, Curie's son-in-law, established a Betatron at the Institut Gustave Roussy (IGR) in 1953 to treat patients. A medical physicist was needed to calculate the patient dose distributions. Andrée Dutreix (neé Sigonneau) fearlessly took on this role as one of the first medical physicists in Paris using the FORTRAN code, also to calculate brachytherapy dose distributions in the 1960s [16]. She later married Jean Dutreix, a storied radiation oncologist who even sought training with Louis de Broglie (Nobel Prize in Physics 1929).

Rosalyn Sussman Yalow grew up with modest means and was inspired to pursue science upon reading a biography on Marie Curie and attending a colloquium by Enrico Fermi. While pursuing a Ph.D. at the University of Illinois at Champaign-Urbana, she was the only woman of the 400 faculty members. After earning a doctorate in nuclear physics, she moved back to New York in 1945 and volunteered to work with Quimby at Memorial Hospital to improve her laboratory skills. There, the medical physicist director Gioacchino Failla recruited her to the Bronx Veterans Administration Hospital to set up a radioisotope service. At the VA she became pregnant. Their extant policy was that women had to leave once they were five months pregnant – she ignored it [17]. She is quoted as saying, “The only difference between men and women in science is that the women have the babies. This makes it more difficult for women in science, but… it is merely another challenge to be overcome.” At the VA her research acumen blossomed where she furthered the development of the radioimmunoassay technique. She applied this technique to insulin (her husband was a diabetic), demonstrating that Type II diabetes was not due to insulin production, but due to an antibody rejecting it. For this work and generalizing the technique [18], Yalow shared the 1977 Nobel Prize in Physiology or Medicine and is considered the mother of endocrinology. She is also quoted [17] as saying, “The world cannot afford the loss of the talents of half of its people if we are to solve the many problems which beset us.”

More recently, there are many others who have made substantial contributions to the field of brachytherapy. Marilyn Stovall developed computerized brachytherapy treatment planning methods [19, 20] with fellow medical physicist Bob Shalek at the MD Anderson Cancer Center, and is mostly recognized for studying radiation epidemiology to associate radiation dose with clinical outcomes such as radiation toxicities and tumor control [21].

Monique Pernot instigated several long-term brachytherapy-oriented clinical trials of hundreds of patients in Nancy, France for a variety of disease sites [22] and developed plastic molds for brachytherapy applicators, 30 years ahead of the current push in brachytherapy for patient-specific 3D-printed applicators.

Judith Stitt’s passion was orchids and social justice as well as developing the Madison System for cervical brachytherapy to addresses HDR brachytherapy capabilities such as dose optimization and differing applicator geometries [23, 24] with Bruce Thomadsen and her senior radiation oncologist Dee Buchler, who was a strong women’s advocate and board-certified in gynecology surgery, medical oncology, and radiation oncology [25, 26]. Equally important, Stitt was the first female radiation oncologist to serve on the U.S. Nuclear Regulatory Commission’s Advisory Committee on the Medical Uses of Isotopes towards setting national regulatory and safety standards [27].

Jean St. Germain was a medical physicist at Memorial Sloan Kettering Cancer Center who examined the benefits of radiotherapy for pediatric patients like Pernot and evaluated radiation safety for an assortment of therapy and imaging modalities including brachytherapy [28, 29]. St. Germain was inspired by Curie and was fortunate to have spent time with her daughter [30]. Her further passions included opera where she was a Juilliard-trained soprano soloist who frequently gave recitals in New York City.

Christine Haie-Meder’s career blossomed over 30 years ago at the IGR where she built upon the deep experience of the French radiation oncologists in treating most any cancer with brachytherapy in a scientific manner. She has developed numerous clinical trials and led European efforts to compare brachytherapy with external-beam radiotherapy for improved outcomes. Through these efforts, she helped transition IGR from using low-dose rate (LDR) sources to high-dose rate (HDR) remote afterloading with dose optimization with improved dose conformity and has coordinated Groupe Européen de Curiethérapie activities to set common standards for gynecological brachytherapy and with magnetic resonance imaging(MRI)-guidance [31, 32].

Patricia Eifel is a Stanford-trained radiation oncologist who served as faculty on the Harvard Medical School and has been at the MD Anderson Cancer Center in Texas, U.S. for over 30 years. She was the first woman to be awarded the Henschke Award by the American Brachytherapy Society (ABS) in 2010, served as President of the ABS and ASTRO, and was awarded the ASTRO Gold Medal in 2018 [33]. Eifel sought brachytherapy training at IGR, developed several gynecological practice standards with the U.S. National Comprehensive Cancer Network [34], discovered the utility of concurrent chemotherapy in combination with brachytherapy for the treatment of cervical cancer [35], and developed a shielded applicator for cervical brachytherapy that is compatible with CT imaging [36], paving the way for conformal brachytherapy with shielding and deviations from the AAPM TG-43 dose calculation formalism where the patient and applicators are assumed to be water equivalent [37-40].

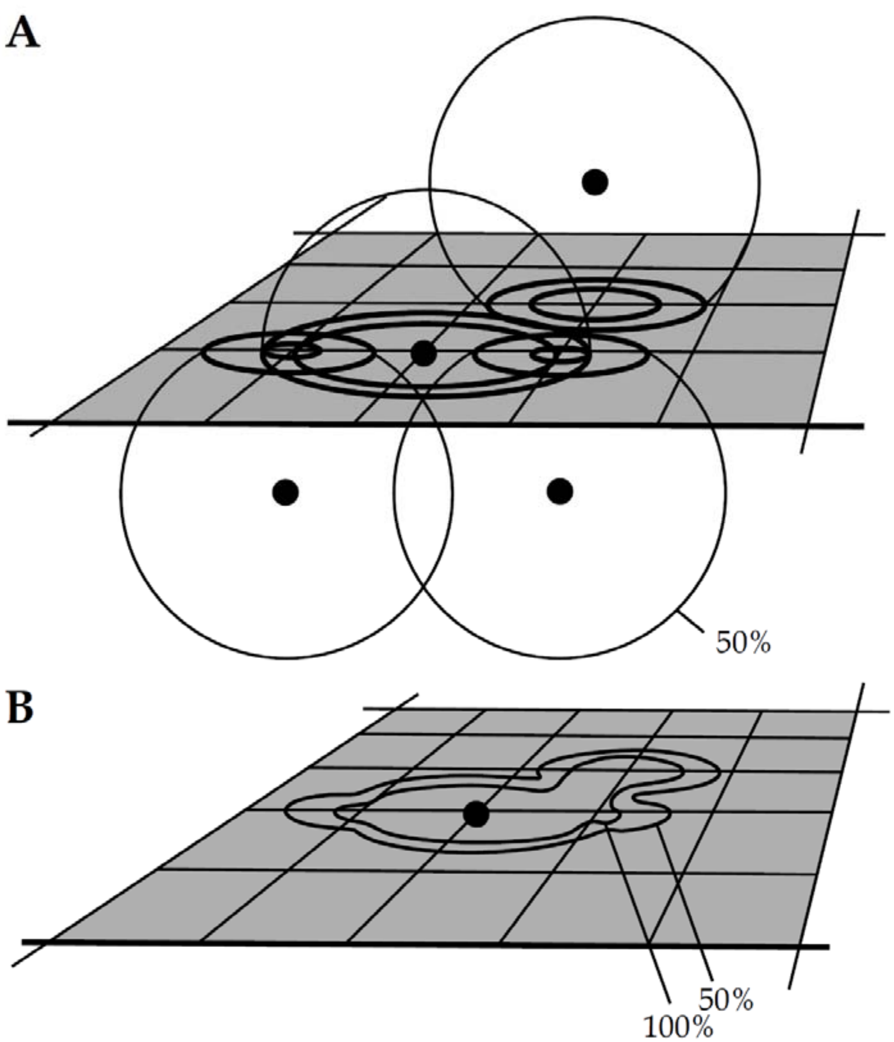

Fig. 2. (A) Assuming spherical dose distributions, doses from four brachytherapy sources are summed onto an arbitrary plane showing the 50% isodose line at the exterior. (B) Removing the 3D perspective, the 100% and 50% isodose lines are depicted. Adapted from Fig. 2 of Aronowitz and Rivard 2014.

3. SOCIAL CONTEXT AND CURRENT ENVIRONMENT

It is hard to appreciate the circumstances many of these women lived in. They must have felt like the outsider in their professional pursuits, often actively being repelled and ill-treated by their male counterparts. These women innovators would recount the few, but rare, allies that supported them and championed their pursuits, though more times than not gender oppression was an unwelcome friction throughout their entire lives [41]. In contrast to the solitude many women endured in the past to be the first in their fields, today more than half of the graduating classes of U.S. medical students are women [42]. This number seems impressive, though a closer look will reveal that the treatment and expectations of women in the classroom and clinic still have a long way to go toward where we should be as a society. As best they could, women have continually challenged the societal pressures against them and have actively pushed the field forward with inclusion, diversity, equity, and accessibility [43].

A prominent challenge for women is to simultaneously manage working while having children. It is often termed "having a family" since the expectations are that she will both create and rear the children as well as maintain the home front. Parenthood brings a whole plethora of unpaid labor that women often take the brunt of, creating an additional barrier to advance in their careers. Across virtually all professions, women are underpaid compared to their male counterparts [44], so adding on the societal pressures that women need to choose between their families and professions (or somehow do the work of two people) makes advancement nearly impossible. When a woman chooses to pursue both work and motherhood with equal vigor, she may be deemed either a *bad mom* or *too work oriented*.

Breaking down these stereotypes and overall misogyny is still a work in progress, though compared to the stone-faced perseverance of the revolutionary women in the past, today there are professional groups that provide a modern networking environment for support and advancement. The International Union for Physical and Engineering Sciences in Medicine has a standing Task Group (Women in Medical Physics and Biomedical Engineering) that strives to increase the visibility and participation of women, supports education and training through focused activities, and gathers data and networks with other groups to push for gender equity [45, 46]. The AAPM formed the Women's Professional Subcommittee in 2017 and has made advances for gender equity in medical physics and promoted women within AAPM leadership positions [47, 48]. Formed in 1997 as a hybrid of three prior organisations, just last year the Institute of Physics and Engineering in Medicine elected its first female president. There is also the Society for Women in Radiation Oncology, who have developed a social media campaign #WeWhoCurie in 2018 that creates a space for women to connect and celebrate women's achievements [49]. While not specific to women, the ABS recently created a Diversity and Inclusion committee as has been common by other societies in the past decade. Organizations such as these and programs recognizing and encouraging women in science are helping to increase gender equity with fewer societal barriers. This approach of course cannot be the sole driver as progressive attitudes and male allies are equally needed to support women in the workplace. Men still hold the majority roles of power and oppression can also come from fellow female counterparts. In light of all the hurdles (past and present), it is inspiring to recount the work of groundbreaking women that moved brachytherapy forward and inspired generations of women scientists.

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THE EXCEPTIONALS: WOMEN JOURNAL EDITORS IN THE FIELD OF MEDICAL PHYSICS

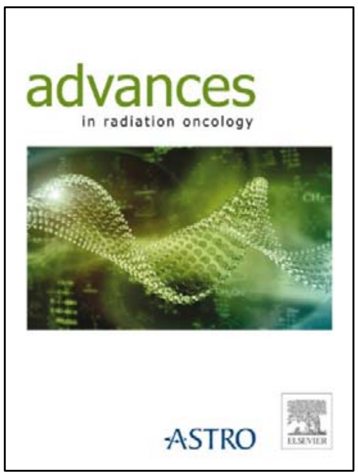
Chiaojung Jillian Tsai, MD, PhD and Kathleen Marie Hintenlang, PhD, FAAPM, FACR, FASTRO

ASTRO Advances Deputy Editor-In-Chief and Senior Editor-Physics / IOMP Women Subcommittee

1. Foreword

Three decades ago, the very first invited oral presentation Kathleen M. Hintenlang, PhD was honored to present at a State society was entitled 'Women in Science'. The presentation referenced published and unpublished masterworks of pre-eminent scholars: Marie Curie, Lise Meitner, Irene Joliot-Curie, Tikvah Alper, Edith Quimby, Chien-Shiung Wu, Rosalind Franklin, Ida Noddack, Rosalyn Yalow. There were many women whose accomplishments were not captured, and others lost in the pages of history. Come full circle and IOMP is celebrating its 60th anniversary with a published issue of the MPI Journal History Edition dedicated to this anniversary.

We are proud to introduce you to the exceptional women journal editors that are continuing to inspire, motivate and lead the way, as they provide an historical view of their journal's development along with perspectives.



***Advances in Radiation Oncology**,* established in 2015, is the first Gold Open Access, peer reviewed journal from the American Society for Radiation Oncology (ASTRO). Included in PubMed Central, *Advances* complements the research in the International Journal of Radiation Oncology • Biology • Physics and Practical Radiation Oncology. The mission of *Advances in Radiation Oncology* is to address the rising demand for outlets to publish quality radiation oncology related research and limitations in the number of manuscripts that could be published in conventional paper journals. As the journal contents are permanently and freely available online, Advances can be accessed on a global basis to all health care professionals and scientists, as well as our patient population and their caregivers. Additionally, one of the goals of Advances is to address contemporary pressing issues pertinent to all aspects of cancer care, including technologic innovations, COVID-19 pandemic, cybersecurity, and the impact of artificial intelligence in academic publishing.

2. Susan Richardson: Journal of Applied Clinical Medical Physics

Susan Richardson

I'm Susan Richardson, Ph.D., the newest Deputy Editor of the American Association of Physicists in Medicine (AAPM) **Journal of Applied Clinical Medical Physics (JACMP)**. Prior to my current role I have been an associate editor for many years, and an active reviewer. While JACMP has always been supportive of women in medical physics, I am also proud to be the first woman associate editor.

One of the ways JACMP support women in medical physics is through their double-blind review system. Studies have shown that journals with a single-blind system (the reviewers are hidden from the authors) demonstrate a bias during the review process. Samantha Hedrick and I wrote an editorial regarding this earlier this year (1). Such a bias, whether conscious or unconscious, tends to discriminate against women. Even reviewers who are not explicitly biased against women tend to favor well-known authors. Unfortunately, such a bias also works against women as the medical physics field has historically (and continually) been overrepresented by men. The most effective solution to overcoming these biases is a double-blind review process which hides the authors from the reviewers as well as the reviewers from the authors. This addresses both the bias against women and the bias against less well-known authors (who also tend to be women). This is one of the many reasons I am excited to help lead JACMP in my role as Deputy Editor.

JACMP also supports women medical physics in another way. Historically women have taken a greater proportion of clinical roles, often as M.Sc. physicists. With its focus on clinical articles JACMP provides an excellent forum for those physicists to publish. The open access model of JACMP also supports visibility of authors. Since published papers are often judged by the quality of the journal they are published in, my mission is to help JACMP continue its excellent reputation, which includes the journal impact factor but also in other metrics. Another aspect of an excellent journal is the shortened time from submission to publication. Authors look at the time involved getting their manuscript through the review process and sometimes choose the journal based on how streamlined that process is. I want to make JACMP's review process as painless as possible. We strive to obtain appropriate and comprehensive reviews at JACMP both by ensuring prompt review of submissions as well as making improvements to the web site both for authors and reviewers.

(1) Hedrick, Samantha G., and Susan Richardson. "EDI and open access: How JACMP is the future of ethical publishing—A tale in two parts." *Journal of Applied Clinical Medical Physics* 23.11 (2022). https://doi.org/10.1002/acm2.13818

3. Iuliana Toma-Dasu: Physica Medica - European Journal of Medical Physics

Uiliana Toma-Dasu

Physica Medica - European Journal of Medical Physics (https://www.physicamedica.com/), the official journal of the European Federation of Organisations for Medical Physics (EFOMP), the Associazione Italiana di Fisica Medica e Sanitaria (AIFM), the Société Française de Physique Médicale (SFPM), the IrishAssociation of Physicists in Medicine (IAPM), the Czech Association of Medical Physicists and the Hellenic Association of Medical Physicists, has a long history of serving the medical radiation physics community by publishing articles on the main topics related to the major areas of scientific and professional activities of medical physicists, such as radiation therapy, diagnostic and therapeutic nuclear medicine, diagnostic and interventional radiology as well as magnetic resonance imaging and complementing fields.

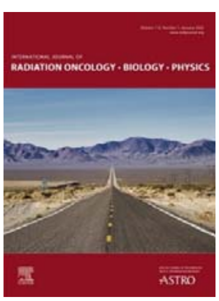
The long journey of Physica Medica to become the flagship publication of EFOMP and play the important role it has today in the European medical physics societies, started in Italy and the first recognition of its impact to the scientific literature in the field came as early as 1996 when the journal gained its first Impact Factor. Since 2007 Physica Medica is publishing with the well-known academic publishing company, Elsevier. The journal consolidated its position, developed, and had a steady growth with Prof Alberto Del Guerra (Pisa, Italy), Prof

Fridtjof Nüsslin (Munich, Germany) and Prof Paolo Russo (Napoli, Italy) at the helm, sailing through the complicated waters of the challenging field of medical physics. This would not have been possible without the voluntary support of the members of the editorial board from all over the world, the ever growing pool of highly competent reviewers and, last but definitely not least, without the contribution of our published authors, who are deeply acknowledged. The current status of the journal is making us proud: the number of submissions is continuously increasing - by a factor as great as 10 from 2010 to 2020 - the IF has broken the glass ceiling reaching 3.119 in 2022, and the most updated CiteScoreTracker for 2022 is 5.6. We reached in terms of submissions and citations far away from the European borders, making thus Physica Medica the journal of a much larger community than the European one in the true spirit of cooperation that we promote and actively support.

It was therefore a great honour to me to be invited in 2021 to get on board of Physica Medica and bring my own contribution as Editor in Chief to the development of the journal, after years of collaboration as reviewer and Associate Editor. I experienced it as a challenge and great responsibility requiring not only competence, but also commitment and dedication, and, to some degree, some sense of vision for what the future might bring into our field in order to make sure that the ship is not only sailing smoothy through its familiar waters, but it is also opening new ways. This translates into publishing not only the traditional work in medical physics on dosimetry, imaging and technology, which is the core of research and development in our field, but also papers that involve close collaboration with our colleagues the medical doctors, as well as publications crossing the bridge towards radiobiology, radiation protection, modelling, and the use of Artificial Intelligence to mention just few examples. To ensure sustainable integration of our profession in the field of health care we plan to foster further the multidisciplinary collaboration and engage more our colleagues the medical doctors, the nurses, the radiobiologists, the engineers, and the radiation protection experts, not only by publishing papers that are addressed to them, but papers that are written by them for the medical physicists. It is my strong belief that only through multidisciplinary collaboration the progress in our field from a theoretical idea to the test bench and the patient bed could be ensured.

Journals like ours are not just the perfect platform for high quality research and development dissemination and educational support, they also act as a mirror of the society they serve. Physica Medica is therefore reflecting with respect and thankfulness the large diversity of the members of the medical physics community without any type of borders worldwide. This is not unique; it is the spirit of The International Organisation for Medical Physics, and it is our ambition to keep promoting it and inspiring the generations to come to carry it on!

4. Samantha G. Hedrick, Sue S. Yom, Hania A. Al-Hallaq: International Journal of Radiation Oncology, Biology, Physics



Samantha G. Hedrick

Sue S. Yom

Hania A. Al-Hallaq

Scientific publishing is an important endeavor for our society, providing data and benchmarks for improving patient care and a path for career advancement for researchers. Ensuring that equity, diversity, and inclusion (EDI) are integrated into scientific publishing is challenging [1], particularly when considering the number of people and steps involved. At each step of the process, there is a need to consider EDI in the data collected and reported, the authors writing the manuscripts, the reviewers providing feedback, and the editors managing the ultimate publication.

EDI provides value to all aspects of science and scientific publishing, and thus should be valued not only as an ethical but strategic imperative. Al Shebli et al found that a paper written by a diverse group of authors is strongly correlated with a higher impact factor than a paper written by a homogenous group of authors [2]. Moreover, a scientist surrounded by a diverse group of collaborators has a higher impact factor than an ethnically similar group of collaborators [2]. However, the current state has room for improvement. For example, Salazar et al found that most editors of top-cited journals are heterosexual, white men [3]. Chatterjee et al showed that research conducted by women receives fewer citations [4]. Hopkins et al reported that there is a disproportionately higher rejection rate for authors from underrepresented groups [5]. Publishing is a hierarchical field, in which one works their way up from author to reviewer to associate editor to the penultimate position of editor. Thus, women and other racial/ethnic and gender minorities must be well represented at all rungs of the ladder in order to be afforded the opportunity to become an editor.

Publishers and journals across various domains of science are now noting the disparities along the author-editor continuum [6]. In evaluating authorship, Kozlowski et al in 2022 found that women are overrepresented as authors in the health sciences compared to the United States population, but are underrepresented in physics and mathematics [7]. In addition, gender disparities have been specifically documented in certain medical specialties, such as radiation oncology [8], and are especially acute in allied fields such as medical physics [9] whose pipelines are inherently skewed [10] . The additive effects of intersectionality, a relatively common state of multiple minoritized identities, enhances exclusion [11]. In medical physics, we may wonder when is the tipping point at which time such gender and racial/ethnic disparities could be expected to improve? Social scientists have discovered experimental evidence demonstrating that a minority opinion must exceed 25% or more in order to change societal norms [12]. However, media research also demonstrates that when the visual representation of women exceeds 33%, it is perceived by men as a majority of women [13]. How does this translate into the world of medical physics publishing?

Scientific journals have acknowledged that it is their responsibility to actively seek a diverse team, outlining five steps that journal editors should take to support social justice including: adding diversity to editorial meeting agendas, diversifying the editorial team and advisory boards, and encouraging editors to actively diversify their contact lists when commissioning editorials, reviews, etc [14]. Double-anonymized review is one way to improve equity and inclusion at the author level [15,16]. In terms of diversity of editorial boards, editors should collect demographic information and actively seek to diversify their cohort. One practical method by which to accomplish this is to impose term limits [17], as the *International Journal of Radiation Oncology, Biology, and Physics (IJROBP)* does. It is understandable that leadership positions may reflect a previous underlying population distribution, but formal mechanisms can be installed which act in support of rapid adaptation and allow for aspirational goal-setting.

Enhancing opportunities for professional growth is another strategy for increasing diversity. In academic medicine where there is significant career longevity, the opportunities afforded to early-career members may be limited as the demographic composition of professionals in a field can change more rapidly than the timeline of career progression (i.e., mostly men to more women). Given that the percentage of women in the American Association of Physicists in Medicine (AAPM) and on the editorial board of *Medical Physics* [10], 23% and 17% respectively, are both below the tipping point (assuming this is 25%), it behooves our male allies in publishing to actively consider diversification of the editorial pipeline. There has never been a female editor of either *Medical Physics* or *JACMP*, whereas analogous European journals, such as *Physica Medica* and *Physics in Medicine and Biology,* currently both have female Editors-in-Chief. At the *IJROBP*, the Editor-in-Chief is likewise female and over the past couple of years the percentages of women at the executive/section editor and associate editor level have exceeded 40-50% including within the physics section [6]. It should be noted that ASTRO has recently initiated processes to collect improved demographic information on its membership, which are intended to facilitate continued diversification of all of its committees, conferences, and journals.

As Dr. Elizabeth Kagan Arleo, Editor-in-Chief of the radiology journal *Clinical Imaging*, pointed out when the field of radiology was grappling with the dearth of female editors of radiology journals [18], “the time is now.” Furthermore, as the late Justice Ruth Bader Ginsburg eloquently reminded us, “women belong in all places where decisions are being made.” If the clinical radiologic sciences can increase the number of women editors-in-chief from none to nine in a matter of a few years [18], it is possible for other health fields to follow suit. Excluding any voice from our community, based on race, ethnicity, gender, or other minoritized identities, potentially discards information and perspectives that are valuable to our communities and patients. The value of including EDI in scientific publishing is enabling more scientists to ask more questions and finding more answers that will help more people.

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5. Katia Parodi – Physics in Medicine and Biology

Katia Parodi

I feel privileged to serve as the first female Editor-in-Chief of the journal **Physics in Medicine and Biology (PMB).** Since its inception in 1956, the journal has promoted the dissemination of cutting-edge research on the application of Physics to Medicine, Physiology and Biology, with special emphasis on therapeutic procedures and medical imaging. While remaining true to its initial mission, PMB has constantly expanded its subject areas to adapt to the evolving scientific landscape of biomedical physics and engineering. In this process, the journal has also adapted its format and is currently a hybrid open access journal, where authors have the option to pay an article publication charge for gold open access.

PMB is published by the Institute of Physics Publishing on behalf of the Institute of Physics and Engineering in Medicine, which are both not-for-profit companies committed to use the revenue generated by the journal to promote global advancement and dissemination of science. In line with the principles of these two institutes, PMB is engaged to promote diversity, equity and inclusion in scientific publishing, and this is well reflected by the constant efforts to ensure equal opportunities for researchers to become authors, reviewers or editorial board members, along with the support offered to researchers based in lower-income countries for affordable open access publication of their work.

The dynamic and open-minded spirit of the journal has not only contributed to a wide scientific and geographical spread of the international editorial and advisory boards but has also supported an increasing engagement of women in leading positions for the journal over the last decades.

For many years, several female scientists including myself have served or are actively serving the journal in key positions and can thus actively contribute to solicit, review rigorously and disseminate quickly and broadly the best new science in our field, helping to shape the future of Medical Physics and bridge more fundamental research into novel applications of Physics to Medicine, Physiology and Biology.

6. Marianne Aznar – Radiotherapy and Oncology

Marianne Aznar

Radiotherapy and Oncology publishes papers relating to radiation oncology, including clinical radiotherapy, combined modality treatment, experimental work in radiobiology, chemobiology, hyperthermia and tumour biology, as well as physical aspects relevant to oncology, particularly in the field of imaging, dosimetry, and radiation therapy planning.

I joined “Radiotherapy and Oncology” as physics editor in 2020: though I was the first women in this role, it is worth noting that prof David Thwaites was the first and only physics editor for many years from 1994! (https://doi.org/10.1016/j.radonc.2020.11.005.).

At present, only 5/15 editors and 21/72 editorial board members of Radiotherapy and Oncology are female. Though the publisher, Elsevier, and the editorial office are aware of the need for more gender balance (https://www.elsevier.com/about/press-releases/corporate/elseviers-journals-now-displaying-editors-gender-in-support-of-diversity), this lack of representation will take time to resolve as members and editors are appointed for a fixed number of years: gradually, as people rotate out of their editorial functions, more women can be invited to contribute. It is worth noting that no such data is collected for reviewers.

Though it is understandable, it is also makes it hard for editors such as myself to ensure diversity when inviting reviewers to comment on an article.

7. Magdalena Stoeva – Health and Technology

Magdalena Stoeva

My name is Magdalena Stoeva, PhD, FIOMP, FIUPESM, and together with K. P. Lin, PhD, FIUPESM we are the Editors in Chief of the Journal Health and Technology (HEAL, https://www.springer.com/journal/12553). I also serve as the Secretary General of the International Union for Physical and Engineering Sciences in Medicine (IUPESM).

Being an editor is more than just a job, this is a way we see the world and more important communicate scientific, educational, and professional information to our colleagues and the global scientific audience. Combining the interdisciplinary knowledge of the basic sciences, the novelty trends of the profession, the understanding of the professional challenges our colleagues face, and what is more important, contributing to the establishment and supporting the mechanisms to deliver sustainable professional growth and workplace balance are probably the most important, but also the most challenging tasks an Editor can face.

Health and Technology is jointly published by Springer and the IUPESM in cooperation with the World Health Organization. It is the first truly cross-disciplinary journal on issues related to health technologies addressing all professions relating to health, care and health technology.

The journal constitutes an information platform connecting medical technology and informatics with the needs of care, health care professionals and patients. Thus, medical physicists and biomedical/clinical engineers are encouraged to write articles not only for their colleagues, but directed to all other groups of readers as well, and vice versa.

The journal Health and Technology works in close collaboration with women groups and committees established under the IUPESM, the International Organization for Medical Physics (IOMP) and the International Federation for Medical and Biological Engineering (IFMBE).

I would also like to use the occasion to convey my special gratitude to the female team-members at Springer for their active role in the publishing process throughout the years:

- Chew Juan Low, Senior Editorial Assistant
- Jana Palinkas, Associate Publisher
- Sonal Shukla, Head of Abstracting & Indexing
- Suvira Srivastav, Publishing Director, Mathematics, Physical and Applied Sciences
- Teena Bedi, Senior Publisher, Computer Science and Engineering.

This special article is dedicated to all female editors, associate and senior editors, peer-reviewers and those that contribute towards scientific progress and dissemination through academic publications.

Authors:

Chiaojung Jillian Tsai

Kathleen Marie Hintenlang

WOMEN IN MEDICAL PHYSICS: ADDRESSING THE CHALLENGES, RECOGNIZING THE PROGRESS WITH IAEA

Virginia Tsapaki, Ph.D.[1] and May Abdel-Wahab, M.D.[2]

[1] Dosimetry and Medical Radiation Physics Section. Human Health Division, International Atomic Energy Agency ; [2] Human Health Division, International Atomic Energy Agency

Introduction

Medical physics (MP) is a critical field that applies the principles of physics to healthcare, with applications ranging from radiation therapy and diagnostic imaging to nuclear medicine and radiation safety [1]. Medical physicists (MPs) play a crucial role in the healthcare team, providing essential support to physicians and other healthcare professionals to ensure that patients receive safe and effective treatments [2]. Despite the importance of MP in healthcare, women remain underrepresented in the field. According to a 2019 survey conducted by the International Organization for Medical Physics (IOMP), women represent only 28% of medical physicists worldwide [3]. This underrepresentation is a cause for concern, as it limits the diversity of perspectives and experiences that are brought to bear on scientific and clinical problems.

The International Atomic Energy Agency (IAEA) is an international organization established in 1957 with the mission to promote the peaceful use of nuclear energy, nuclear safety, and the non-proliferation of nuclear weapons [4]. The IAEA works with its Member States (MS) and partners to ensure that nuclear technologies and applications are used safely, securely, and for the benefit of humanity. The IAEA's mandate covers a range of areas, including nuclear power and energy, nuclear applications in medicine, agriculture, and industry, nuclear safety and security, and safeguards against the proliferation of nuclear weapons. The IAEA Human Health Division is actively supporting efforts to combat cancer, cardiovascular diseases, malnutrition, and other illnesses by leveraging nuclear and nuclear-related technologies [5]. To achieve this, the Division is providing assistance for projects related to cancer radiotherapy treatment and diagnostic imaging, as well as supporting nutrition centers and human resource development. The division is also involved in creating guidelines and databases, offering quality assurance frameworks and review missions, providing technical and advisory services, and offering dosimetry laboratory services. Finally it is engaged in educational and research initiatives to enhance the capacity for effective disease prevention and treatment [6-8].

The IAEA recognizes the importance of promoting gender equality and diversity in all areas of its work. The IAEA has identified that the underrepresentation of women and other underrepresented groups in all fields including medical physics poses a significant challenge for the field, and that there is a need to take proactive measures to address this issue.

IAEA initiatives on promoting gender equality and diversity in MP

The IAEA has developed a range of initiatives aimed at promoting gender equality and diversity in all fields including MP. These initiatives involve training and professional development opportunities, mentorship programs, and networking events.

1. <u>Education and Training</u>

IAEA provides academic scholarships to students pursuing medical physics degrees or related fields. The organization supports the Master's Programme in MP, run jointly by International Center for Theoretical Phsyics (ICTP) and the University of Trieste in Italy [9]. It is a two-year programme that includes one year academic training with basic and advanced courses, followed by a year of clinical training in a MP department of a hospital. The programme is based on IAEA MP education and clinical training material and helps address the scarcity of qualified and well trained MPs, a situation common to many countries. The programme is running since 2014 with a total of approximately 140 graduates two thirds of which are men and one third are women. Figure 1 shows the percentage of women graduates from the ICTP MP programme during the years 2014-2021 from different geographical regions and Figure 2 presents the number of women and men graduates during the years 2014-2021.

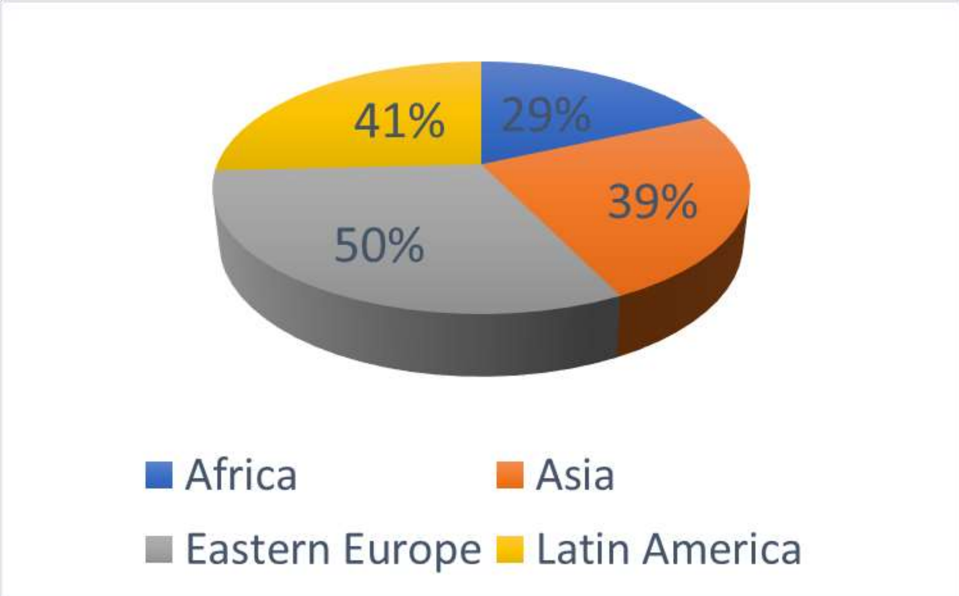

Figure 1. Percentage of women graduating from the ICTP MP programme during the years 2014-2021.

Figure 2. Number of ICTP women and men graduates during the years 2014-2021.

As shown in Figures 1 and 2, women were underpresented in the programme but this trend is apparently changing over the recent past.

One of the IAEA key programmes launched in March 2020 is the Marie Skłodowska-Curie Fellowship (MSCF) Programme [10]. The academic scholarships provided through the MSCF Programme can help to support the careers of women and promote gender equality and diversity in the field. Selected students receive a scholarship for Master's programmes in nuclear related studies at accredited universities. They are also provided with an opportunity to pursue an internship facilitated by the IAEA for up to 12 months. The MSCF Programme will contribute to a new generation of women science leaders including MP, who will drive scientific and technological developments in their countries. Scholarships are awarded annually to 100 plus students depending on the availability of funds. Consideration is given to field of study, and geographic and linguistic diversity. Following the inaugural solicitation for applications in 2020, a total of 360 candidates were chosen to participate in the programme. Among these participants, 44 young female scholars were awarded fellowships specifically for the field of MP; forteen (14) in 2020, 11 in 2021 and 19 women in 2022.

In addition to providing academic scholarships, the IAEA also offers a range of training and professional development opportunities for women in medical physics including fellowships, online or onsite training courses and workshops on a range of topics. These opportunities are designed to help women in medical physics to develop the skills and expertise they need to succeed in their careers and advance in the field. By providing access to training and professional development opportunities, the IAEA is helping to ensure that MP are well-equipped to address the complex challenges faced by the field.

2. Guidelines, conferences related to MP

The IAEA Dosimetry and Medical Radiation Physics (DMRP) Section lies within the Human Heatlh Division and is responsible for all quality assurance (QA) aspects of the use of radiation in medicine to ensure safety and effectiveness, and deals with the science and technology involved in this area. DMRP is involved in many activities, including education, training, research and service provision. Some of its many activities include developing guidelines and recommendations, organizing and conducting educational programs and training courses for medical physicists, and undertaking research projects to advance the field of medical radiation physics and dosimetry and quality assurance. The section organizes the International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS). Figure 3 presents the statistical data on women and men participation during the last years (IDOS 2010 and IDOS 2019). As seen in Figure 3, the representation of women has experienced a modest augmentation, rising from 30% to 32%;

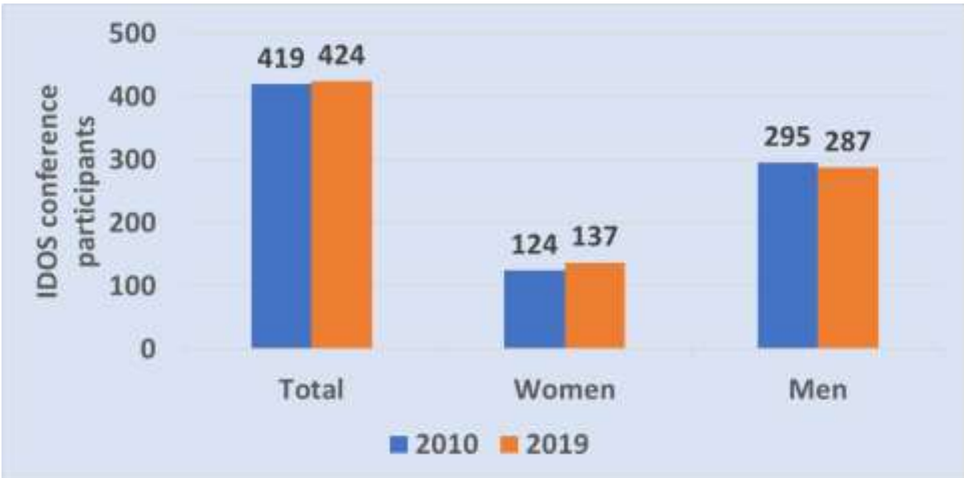

Figure 3. IDOS statistical data for the years 2010 and 2019.

A salient exemplar that mirrors the DMRP's endeavors concerning gender diversity is the heightened involvement of women specialists having a core role in the formulation of guidelines. As delineated in Figure 4, the proportion of women amongst the expert panel involved in drafting guidelines has experienced a marked ascension during the last 3 years. This aspiration necessitates continued dedication to enhancing the representation of women, thereby fostering an equitable distribution of expertise within but also outside the organization.

Figure 4. Percentage of women experts with a core role in drafting the publicationby DMRP, IAEA.

3. Mentoring programme

Mentorship plays a critical role in promoting gender equality and diversity in MP. Research has shown that mentorship can help to increase the representation of women in science and engineering fields by providing support, guidance, and career advice. The IAEA's mentorship program was launched earlier this year (2023), called the IAEA Lise Meitner (LM) Programme, that provides early- and mid-career women professionals with opportunities to participate in a multiweek visiting professional programme and advance their technical and soft skills [11]. The LM Programme envisages enhancing participants' soft skills through management and leadership training, mentoring, networking and coaching, and competency management. The visiting professional programme typically lasts between two to four weeks and possibly longer in some host countries, gathering 10 to 15 visiting professionals per cohort.

4. Networking events

In addition to providing training and professional development opportunities, the IAEA has also established a range of networking events [12] and social media groups [13] aimed at promoting gender equality and diversity in all fields including MP. These events provide opportunities for women in the field to connect with one another, share their experiences, and build professional relationships. By creating a supportive and inclusive community, the IAEA is helping to promote gender equality and diversity in medical physics and providing a platform for women in the field to succeed.

Challenges and barriers to promoting gender equality and diversity in medical physics

Despite the IAEA's efforts to promote gender equality and diversity in MP, there are still significant challenges and barriers that must be addressed. Societal and cultural factors, biases and stereotypes, and structural barriers can all contribute to the underrepresentation of women in MP.

One challenge is the lack of women role models and mentors in the field specially in leading positions. Research has shown that women are more likely to enter and succeed in male-dominated fields when they have access to female role models and mentors [14]. It is anticipated that the IAEA's mentorship program will help address this challenge by providing aspiring women MPs with access to experienced mentors who can provide guidance and support.

Another challenge is the prevalence of biases and stereotypes that can limit women's opportunities and hinder their advancement in the field. Research has shown that unconscious biases can influence hiring decisions, performance evaluations, and promotions, which can have a significant impact on women's careers [15]. The

IAEA's initiatives to promote gender equality and diversity, including its training and professional development opportunities and networking events, are helping to raise awareness of these biases and promote a more inclusive culture, also in the field of MP.

Conclusions

The IAEA has undertaken various initiatives to promote gender equality and diversity, including training and professional development fellowships and opportunities, mentorship programmes, and networking events. These initiatives are critical for ensuring that women have the support and resources they need to succeed in the field and for promoting a more inclusive and diverse culture. While progress has been made in promoting gender equality and diversity including the field of MP, there are still significant challenges and barriers that must be addressed. By continuing to develop and implement initiatives aimed at promoting gender equality and diversity, the IAEA can help to ensure that also the MP domain benefits from the diverse perspectives and experiences of women and other underrepresented groups. Future actions and initiatives should aim to build on these successes and further promote gender equality and diversity.

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WOMEN IN MEDICAL PHYSICS AND CONTRIBUTIONS THAT SHAPED THE PROFESSION IN AUSTRAL-ASIAN COUNTRIES

Magdalena Stoeva, Eva Bezak, Rajni Verma, Chai Hong Yeoung, Hasin Anupama Azhari, Zakiya Al Rahbi, Loredana Marcu
Members of IOMP Women subcommittee

1. Introduction

Historically, women have made a huge progress in STEM. Women's role in science can be traced back to ancient times. The role of the women in medical physics is indisputable, with contribution to every aspect of the profession - education, research and development, clinics, professional development.

However, the proper workplace balance and acknowledgement of female contribution turned out to be a challenging task in certain times and regions. Therefore in 2013 the International Organization for Medical Physics (IOMP) joined forces towards formalizing its support for women in medical physics and established the Women in Medical Physics Group which later-on grew to a Sub-committee (https://www.iomp.org/iomp-w/).

The initial talks were held in 2013 during the International Conference for Medical Physics in Brighton, UK. The idea received unanimous support by the IOMP President prof. K. Y. Chaung, Vice-President prof. Slavik Tabakov and the entire ExCom. The activities related to preliminary analysis, establishing objectives and creating the basics for the international networking were undertaken by Virginia Tsapaki, Simone Kodlulovich and Magdalena Stoeva. The official establishment of the Women Subcommittee (IOMP-W) under the IOMP is the most active step the organization took towards supporting the gender balance in the profession.

The Women Subcommittee was charged with the functions to:

- Develop, implement, and coordinate tasks and projects related to the role of females in medical physics scientific, educational and practical aspects.
- To disseminate the experiences, good practice and learning within IOMP NMOs and other relevant accessible areas/across the globe.
- Popularize the role of the women in medical physics and encourage female medical physicist to advance in the profession.
- Organize international cooperation in medical physics and related specialities.
- Provide regular status/progress updates to the IOMP on all tasks and projects related to the IOMP Women Group.

As the activities of the committee grew and its regional and functional coverage expanded, it turned into a central networking point to coordinate and analyze various aspects related to the involvement of female professionals in medical physics, including but not limited to international collaboration, awareness campaigns, organizing scientific sessions, publications, workforce data analysis.

IOMP Women will shortly celebrate its 10th anniversary, and this is the right moment to convey special gratitude to IOMP Women Group and Subcommittee members who actively contributed to our common goal during these years:

2015-2018 WOMEN IN MEDICAL PHYSICS SUBCOMMITTEE
Virginia Tsapaki, Chair (Greece)
Simone Kodlulovich, Secretary (Brazil)
Stoeva Magdalena, Website (Bulgaria)
Jamila Al Suwaidi, Calendar (UAE)
Teh Lin (USA)

Nicole Ranger (USA)
Anchali Krisanachinda (Thailand)
Rebecca Nakatudde (Uganda)
Efi Koutsouveli (Greece)
Pola Platoni (Greece)
Guadalupe Martín Martín (Spain)
Francesca McGowan (UK)
Hasin Anupama Azhari (Bangladesh)

2018-2022 WOMEN IN MEDICAL PHYSICS SUBCOMMITTEE
Virginia Tsapaki, (Greece), Chair Jun 2018 - Mar 2020
Magdalena Stoeva (Bulgaria), Chair Apr 2020 - Jun 2022
Laura Cervino (USA)
Simone Kodlulovich (Brazil) – SG
Anchali Krisanachinda (Thailand)
Hasin Anupama Azhari (Bangladesh)
Rajni Verma (India)
Nadia Octave (Canada)
Eva Bezak (Australia)
Huda Al-Naemi (Qatar)
Chai Hong Hong (Malaysia)
Zakiya Al-Rahbi (Oman)
Elina Samara (Switzerland)
Savanna Nyarko (Ghana)
Hanan Aldousari (Kuwait)
Lucie Sukupova (Czech Republic)

2022-2025 WOMEN IN MEDICAL PHYSICS SUBCOMMITTEE
Loredana Marcu (Romania) – Chair
Huda Al-Naemi, Qatar
Zakiya Al-Rahbi, Oman
Hanan Aldousari, Kuwait
Hasin Anupama Azhari, Bangladesh
Laurentcia Arlany, Singapore
Eva Bezak, Australia
Kathleen Hintenlang, USA
Simone Kodlulovich, Brazil
Anchali Krisanachinda, Thailand
Savanna Nyarko, Ghana
Nadia Octave, Canada
Elina Samara, Switzerland
Magdalena Stoeva, Bulgaria
Rajni Verma, India
Rafidah Zainon, Malaysia

2. Women in Medical Physics in South East Asia in the past 60 years

In South East Asia (SEA), four women medical physicists have been in the forefront of the development of medical physics in their respective countries. Prof Anchali Krisanachinda, Prof Djarwani Soejoko, Prof Agnette Peralta and Dr Noriah Jamal are the Top 4 women medical physicists in South East Asia (SEA). They have taught or trained many medical physicists and have made the MP profession known in their respective countries. They have inspired female medical physicists in SEA to follow in their footsteps of contributing to the development and promotion of MP in the region.

2.1. Individual Writeups

(I) Prof Dr Anchali Krisanachinda, PhD, THAILAND

Prof Krisanachinda is the most famous and most accomplished woman medical physicist of Thailand. She established the MSc Medical Physics program in 1974 and the PhD Medical Physics program in 2015 in Chulalongkorn University. Together with other MP leaders in the region, she co-founded AFOMP and SEAFOMP in 2000, and the ASEAN College of Medical Physics (ACOMP) in 2014. She was the President of SEAFOMP from 2007 to 2009. She was the founding president of the Thai Medical Physicist Society (TMPS) in 2001. She has organized and chaired multiple local (TMPS) and international (SEACOMP, AOCMP, ACOMP, AAPM/ISEP, ICMP) conferences/workshops.

Prof Krisanachinda has dedicated her life to the development and promotion of the MP profession in her country and in the region. In the latter part of her career, she has focused on helping the less developed ASEAN countries through the education and clinical training of MP from these countries.

For IOMP, she served as the Treasurer from 2012 to 2018, and for AFOMP from 2001 to 2012. In 2013, she was honored as one of the 50 medical physicists of the world who had made "Outstanding Contributions over the Last 50 Years" during the 50th anniversary celebration of IOMP. She received the fellowship award from both IOMP and IUPESM for her outstanding contributions. She received in 2018 - the IOMP Harold Johns Medal , in 2020 - the AFOMP Lifetime Achievement award, and in 2022 - the IOMP International Day of Medical Physics (IDMP) award. She was the SEAFOMP Prof. John Cameron Memorial speaker in 2017 and the AFOMP Prof. Kiyonari Inamura Memorial Oration speaker in 2022. Prof Krisanachinda has served as an expert in multiple IAEA missions. She has been the Project Lead and National Project Coordinator of various IAEA RCA projects.

(II) Prof. Dr. Djarwani Soeharso Soejoko, PhD, INDONESIA

Prof. Soejoko is the pioneer woman medical physicist of Indonesia. She was appointed full professor in medical physics at the University of Indonesia in 2006. She established the BSc Physics major in Medical Physics program in 1998 and the MSc Physics with specialization in Medical Physics in 2002.

She has been the driving force in the development of the MP profession in Indonesia. Together with other MP leaders in the region, she co-founded AFOMP and SEAFOMP in 2000, and the ASEAN College of Medical Physics (ACOMP) in 2014. She received the fellowship award from IOMP in 2019. She received the IDMP award in 2020 for her significant contributions to the profession. Prof Djarwani has served as an IAEA expert in several medical physics missions. She was the National Project Coordinator for multiple IAEA/RCA projects up to 2015. She was the SEAFOMP Prof. John Cameron Memorial speaker in 2012.

She established the x-ray machine compliance testing program under Nuclear Regulatory Agency and has been the chairperson of the government x-ray machine certification scheme since 2012. She also initiated and was involved in drafting government laws and regulations on the use of ionizing radiation in medicine and the role of medical physicists. Due to Prof. Soejoko, the recognition of the MP profession in Indonesia was achieved and the registration of medical physicists by the government commenced in 2012.

(III) Prof. Agnette Peralta, MSc, PHILIPPINES

Prof. Agnette Peralta is the pioneer diagnostic radiology medical physicist (DRMP) in the Philippines, who has taught almost all medical physicists in her country. She has had an important role in the establishment of the MSc Medical Physics program in the University of Santo Tomas in 1981 and in the development of medical physics in her country. Together with other MP leaders in the region, she co-founded AFOMP and SEAFOMP in 2000, and the ASEAN College of Medical Physics (ACOMP) in 2014. She was the President of SEAFOMP from 2013 to 2014. She was the founding president in 1986 of the Philippine Organization of Medical Physicists (now known as the Society of Medical Physicists in the Republic of the Philippines). She has organized and chaired various local and international conferences/workshops in medical physics held in the Philippines.

She was the Director of the Center for Device Regulation, Radiation Health, and Research of the Department of Health, the Philippines for twenty-four years. She retired from government service as an Assistant Secretary of Health, the highest government position ever held by a Filipino medical physicist. She chaired or served in many government committees and task forces. At present, she still teaches in the University of Santo Tomas Medical Physics program on a part-time basis and chairs the subcommittee on clinical equipment and devices of the Health Technology Assessment Council of the Philippines.

Prof. Peralta has served as an expert/consultant for IAEA and WHO. She was elected for three terms as a member of the International Commission on Non-Ionizing Radiation Protection, the only Asian medical physicist to have been an ICNIRP member. She was the National Project Coordinator for two IAEA/RCA projects on education and training of MP. She was one of the examiners for the first board certification examination in DRMP in the Philippines in 2019. Prof. Peralta was awarded the IOMP Fellowship in 2017. She was honoured in 2020 as one of the "Top 21 Outstanding Medical Physicists in the AFOMP Region" on the occasion of the 20th anniversary of AFOMP.

(IV) Dr Noriah Jamal, PhD, MALAYSIA

Dr Noriah Jamal is one of the pioneer women medical physicists in Malaysia. Her career has been dedicated to the promotion and application of physics in medicine, both at the national and the international level. She was the Director of the Division of International Relations and Planning at the Malaysian Nuclear Agency before she retired. She has made major contributions to the academic and professional development of medical physics in her country. She has also organized and directed several national and regional conferences/workshops on radiation protection, diagnostic radiology and nuclear medicine.

She was the Vice Chair of the Medical Physics Division, Malaysian Institute of Physics. She was also the Chair of the Radiation Protection Committee, Malaysia Association of Medical Physics (MAMP). She was the National Project Counterpart of the IAEA/RCA Project RAS6083: Strengthening Medical Physics Through Education and Training (2006-2012). Until the end of 2019, she was the Lead Country Coordinator for the IAEA project RAS6088: "Strengthening the Effectiveness and Extent of Medical Physics Education and Training in the Asia Pacific region." She has served as an expert for IAEA in several missions. Dr Jamal was honoured in 2020 as one of the "Top 21 Outstanding Medical Physicists in the AFOMP Region" on the occasion of the 20th anniversary of AFOMP.

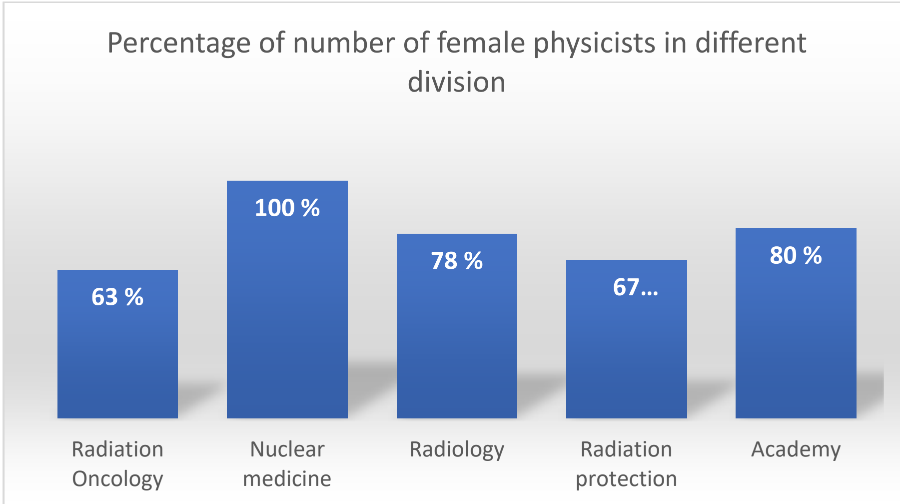
2.2 Other Women Medical Physicists Who Contributed to MP Development in SEA

Other women medical physicists in SEA who contributed to the development of medical physics in the region include Eulinia Valdezco, Lilian Rodriguez, Joyce Melchor, Monica Bacaling, Carmen Mesina, Marilou Rojero, and Aida Lobriguito from the Philippines; Pirunthavany Muthuvelu, Rozana Hussin, Mahzom Pawanchek, Azleen Mohd Zain, Sarene Chu, Nurmazaina Md Ariffin, Jeannie Wong, Chai Hong Yeong, Rafidah Zainon, and Nursakinah Suardi from Malaysia; Ratana Pirabul and Sivalee Suriyapee from Thailand; Ratih Oemiyati, Yekti Nastiti, Rini Shintawati, Darmawati, and Indah Lestariningsih from Indonesia; and Cheryl Lian and Laurentcia Arlany from Singapore.

Dr Chai Hong Yeong is the youngest ever elected President of SEAFOMP (2022-2025). She also holds multiple positions internationally: Chair of the Medical Physics World Board (MPWB) of the IOMP, Founding Committee of the ASEAN College of Medical Physics (ACOMP), Committee Member of the Professional Relations Committee of AFOMP, etc. She is the current Editor of the e-Medical Physics World (e-MPW) bulletin, and the Editorial Board member of the Physics and Technology in Medicine (PTM). She was the Chair of the 18th AOCMP and 16th SEACOMP in 2018 that successfully hosted >550 participants from 40 countries in Malaysia. She has published more than 80 peer-reviewed journals, 2 academic books, 2 book chapters, and has assisted the IAEA in drafting the "IAEA HHS No. 46: Worldwide implementation of digital mammography imaging" and "Quality assurance and optimization for fluoroscopically guided interventional procedures" guidelines. She received the IUPAP Young Scientist Award in Medical Physics 2021, and the SEAFOMP Young Leaders Award 2017.

3. Women in Medical Physics in Sultanate of Oman

In Oman, women represent the majority of the graduates of Sultan Qaboos University in the field of physics / medical physics. Females currently constitute to nearly 80% of the workforce in all medical physics disciplines in the Ministry of Health and Sultan Qaboos University and the Sultan Qaboos Comprehensive Cancer Center as shown in the chart below. The percentage of Omanisation of females in all sub-specialists in the medical physics field reached 100%.



Up until the article was written, there are two female medical physics who successfully achieved doctorate (PhD) level and about 9 physicists have a master's degree. Three of the Omani female physicists who underwent an accredited residency program and one specialized training program after achieving their master's degree.

Female Medical physicists have an effective role in this field as they have contributed to many national and international training programs, conferences and workshops within Oman. Moreover, they continue to participate in the world by celebrating the international medical physics day on 7th November and also breast cancer awareness in October.

Dr **Zakiya Salem Al Rahbi**, Chief Specialist Medical Physicist, works for the National Oncology Center, Radiotherapy Department, Royal Hospital. Dr Al Rahbi is a medical physicist researcher and international speaker and lecturer. Since 2019, she is the coordinator of the Physics program in the Diagnostic residency program at OMSB. In addition, she is assigned to be Radiation Protection Supervisor at the Royal Hospital. She is a deputy president of the Omani Medical Physics Society (OMPS) since 2018, as well as Chairperson of the Award and Honours Committee in the Middle East Federation Organization of Medical Physics (MEFOMP), and a member of the International Organization of Medical Physics- Women Group (IOMP-W) and MEFOMP-W. She has presented several proposals to improve the quality of the workflow and to improve the situation of the Medical Physics field in the Ministry of Health, Oman. Recently, her application to join ICRP Mentorship Program is accepted, and she has been selected to take part in work for Task Group 116 Imaging in Radiotherapy.

Dr **Al Rahbi** is the first Omani medical physicist in the MoH. She has a PhD degree from the University of Wollongong, Australia in 2019 and an MSc degree from the UK in 2009. She underwent a Residency program at King Faisal Specialist Hospital and research center in 2015. She has attended many trainings in her field and gained experience in the field of quality assurance of Radiotherapy modalities, Brachytherapy as well as in radiation safety aspects of workers, patients, and workplace .Dr Al Rahbi has several scientific research, which have been published in international journals in this field. She has participated in many international and national workshops, conferences and presented several presentations and posters. She has participated in several international and national conferences as a speaker or organizer. Additionally, she has conducted several workshops and training courses in and out of Oman. She has participated in many international planning competitions as well and achieved high scores. Currently, Dr Zakiya Al Rahbi is the Chairperson, of the local organizing conference committee, MEFOMP Medical Physics Conference 2023. https://mefomp-conference.com./

Dr Al Rahbi achieved many awards. The highlights of these achievements include the "AOCMP-AMPICON 2017 Best Poster Award",17th Asia-Oceania Congress of Medical Physics "AOCMP – 2017", which was evaluated by the president of the International Organization of Medical Physics and 1st prize in Breast Abstract Presentation', the 5th middle east best of CTRC-AACR, San Antonio BEAST CANCER Symposium .

Her passion does not stop here, she went through the International Medical Physics Certification Board (IMPCB) parts 1 & 2 and passed them with high scores. Her priority is always to update her knowledge and skills in all sub-fields of medical physics by attending plenty of lectures and webinars as well as carrying out research and participating in several international treatment planning competitions .Over the years, she has gained great experience in the field of quality assurance of radiation oncology, radiological diagnostic imaging modalities, as well as in the radiation safety aspects of radiation staff, patients, and the workplace. Besides my residency study, her attachment to the Medical Physics and Radiation Protection department in MoH gave her the opportunity to cover all sub-specialties of the Medical Physics major, as well as the management in medical physics Oman. Dr Al Rahbi has developed several manuals, protocols, guidelines, policies, and procedures based on international standards.

4. Women in Medical Physics in other Austral-Asian countries

Among the most proactive female physicists in promoting and supporting the role of women in medical physics in Austral-Asia is **Eva Bezak**. Prof. Bezak, MSc, PhD, FACPSEM, FIUPESM is an internationally known medical physicist and professor in Medical Radiation at the University of **South Australia** (from 2015). Prior to 2015, she spent 17 years in industry as a medical physicist at the Royal Adelaide Hospital (RAH), becoming Chief of Medical Physics in 2006. She was the first female president of the Australasian College of Physical Scientists and Engineers in Medicine (ACPSEM; 2010-2012) and secured $5.5M of government funding for an Australian medical physics training. In 2015 she was appointed to the Administrative Council of the International Union for Physical and Engineering Sciences in Medicine (IUPESM) and was founding member of the IUPESM Women in Medical Physics and Biomedical Engineering Task Group. In 2017 she became the first female vice president (now president, 2023) of the Asia-Oceania Federation of Organizations for Medical Physics (AFOMP). In 2019 she was appointed the Secretary General of the International Organization for Medical Physics and was elected the IOMP VP in 2022. She is a convenor for the IUPESM World Congress 2025, to be held in Adelaide, Australia.

Eva is a co-author of the Australian Academy of Science Report on future accelerators in Australia (2016) informing the government on the need for proton therapy and a past member of the National Radiation Oncology Tripartite Committee that developed quality and performance standards for radiation oncology in 2012 directly impacting the

quality and the delivery of radiation oncology services in Australia. She co-authored the Tripartite National Plan for Radiation Oncology 2012-2022 as well as the National Needs Analysis Survey, examining accessibility to antenatal ultrasound and training in rural Australia (2022). Additionally, she is an author of over 200 publications and 3 books and has supervised over 40 research postgraduate students (MSc, PHD).
In 2019 she was included in the South Australian Women's Honour Roll, tributing South, Australian women who have made a significant impact on the community, women who are role models and leaders.

Representing **Bangladesh**, Prof. **Hasin Anupama Azhari** is currently serving as Vice-President of AFOMP and Member of IOMP Women Subcommittee. She is involved as Associate Editor of European Journal of Medical Physics (Physics Medica). She was the chairperson of several national and international medical physics conferences. In addition, she was the chair of many scientific sessions related to medical physics (e.g. AOCMP 2019, 2021, 2022, AMPICON, EPSM, IUPESM WC etc).

From the early years of medical physics in **Iran**, women were actively involved in such roles as Vice-President of the first IAMP ExCom (Prof. R. Bagherzadeh Akbari), etc. Nowadays, female Iranian medical physicists have further leading roles, such as membership of an AFOMP committee (Prof. P. Mehnati), journal editorial boards, conference scientific/organizing committees, and university faculty (including many full professors) as well as authoring books/papers, chairing departments and research centers, etc. (e.g., Professors P. Shokrani, M. Mokhtari-Dizaji, A. Sazgarnia, S. Khoei, N. Gharehaghaji, S.M. Hejazi, etc). About 50% of IAMP members and Radiotherapy Physics Board certificate holders are female. Also, those living abroad hold further leading positions.

In **India**, women in medical physics have recently started to come to leadership positions in professional fronts apart from some very few exceptions, due to male dominance and traditional mindset of the society. Dr **Rajni Verma** is the first and the youngest women medical physicist as member to various AFOMP and IOMP committees and working groups. Since 2018 she is actively involved in all activities related to women participation in medical physics organized by the IOMP Women subcommittee, which include special session in international conferences. Rajni is also an active member of the IOMP website committee, contributing along with other members of group to design and develop the contents for the website. Mainly focused on aim of "space for all" and encouraging the peers globally to report the activities. As the first female to this position, in 2018 she became the AFOMP website manager, while during COVID-19 she got actively involved in materializing the idea of virtual academic programs AFOMP Monthly webinar (since June 2020), AFOMP School Webinar (since June 2021) which are running successfully till date and proved to be one of the key academic programs of AFOMP. Rajni is also a member of the IOMP Medical physics World Board subcommittee which handles the IOMP newsletter, website, webinar and social media. On a national level, Dr Verma is a member of the Executive Committee of the Association of Medical Physicist of India-Northern Chapter, working on the development of member directory for the chapter and regularizing academic events, also being involved in the celebration of International Day of Medical Physics on Chapter level every year (since 2017), working to digitalize it on several social platforms for better recognition of medical physics community within the nation.

THE HISTORY OF ESTABLISHMENT OF THE INTERNATIONAL DAY OF MEDICAL PHYSICS

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Abstract:
In connection with the first 10 global celebrations of the International Day of Medical Physics (IDMP), the article lists the events, which triggered the creation of the IDMP by the International Organization for Medical Physics (IOMP). The processes and people associated with the establishment of the IDMP on 7 November – the birthday of Maria Skłodowska-Curie, as well as the following establishement of the IDMP Award of the IOMP are also presented.

Keywords: Medical Physics, International Day of Medical Physics, IDMP, IOMP

I. Introduction

The International Day of Medical Physics (IDMP) was triggered by the announcement in 2011 of the recognition of the professional occupations of *medical physicists* and *biomedical engineer*. This great success for the profession was of huge importance for the colleagues from Low and Middle Income (LMI) countries, where the professions were not included in the registries of the respective Ministry of Labour and the colleagues were employed under various titles not directly linked with the profession.

The International Union of Physical and Engineering Sciences in Medicine (IUPESM – the Union between IOMP and IFMBE) started discussions with the International Labour Organisation (ILO) immediately after its achievement of becoming full member in 1999 of the International Council of Scientific Unions (ICSU, now ICS), thus including medical physics and biomedical engineering as separate scientific fields [1].

The discussions with ILO aimed inclusion of the professional occupations medical physicist and biomedical engineer in the International Standard Classification of Occupations (ISCO), each with its unique code – and ID for each profession respected by all Ministries of Labour. These negotiations took many years and included several officers of IUPESM, most active were Azam Niroomand-Rad, Fridtjof Nuesslin, Peter Smith and Slavik Tabakov. Finally in 2011 it was announced that ILO has included ISCO-08 the professional occupation medical physicist under category 2111 and biomedical engineer under 2149 [2, 3].

IOMP was seeking ideas how to celebrate this great achievement. The idea came in 2012 from the Latin American Association of Medical Physics (ALFIM). A colleague from Venezuela Mr Julio Pinuela proposed to the then President of ALFIM Dr Simone Kodlulovich Renha the idea to have a professional day (as various other professions have). Dr Renha discussed this with the then IOMP President Dr Fridtjof Nuesslin, who fully supported it and proposed it to the ExCom of the International Organisation of Medical Physics (IOMP) during the spring of 2011. The idea of a professional day was immediately supported by all members of the IOMP Executive Committee (ExCom).

II. The selection of the IDMP Date and professional patron

The initial ideas about the date of the IDMP included the end of August (related to the important meeting in Montreal on 26 August 1962, when an International Steering Committee decided to form IOMP from 1 January 1963). However a date in August was seen as unpractical as many colleagues are on vacation at that time.

At the IOMP ExCom meeting on 26 May 2012 (at the World Congress in Beijing), a new date emerged – 8 November (related to the discovery of X-ray by W K Roentgen). It was decided the first IDMP celebration to be in 2013 to additionally celebrate the 50th Anniversary of IOMP.

However, several months after this it appeared that by coincidence at the same time the European Society of Radiology (ESR), the Radiological Society of North America (RSNA), and the American College of Radiology

(ACR) are discussing the establishment of the International Day of Radiology (IDoR) exactly on 8 November (it was first celebrated on 8 November 2012 and continues to this day) [4]. These discussions were related to the already celebrated by ESR European Day of Radiology on 10 February 2011 (the first and only such celebration, commemorating Roentgen's death). It also appeared that 8 November is already celebrated by the International Society of Radiographers and Radiological Technologists (ISRRT) from 2007 as World Radiography Day [5]. Thus, IOMP had to look for another suitable date for the IDMP.

At the IOMP ExCom meeting on 19 July 2012 the new ETC Chair Dr John Damilakis was charged with the organisations and coordination of the first IDMPs. The new idea for the date of the IDMP came on 19 October 2012 at the VIth European Conference of Medical Physics in Sofia, Bulgaria. This event was attended by a group of several IOMP officers – Slavik Tabakov (Vice-President), Madan Rehani (Secretary General), John Damilakis (ETC Chair) and Virginia Tsapaki (MPWB Chair). Dr John Damilakis proposed to the group several alternative dates, associated with the pioneers of radiation, and all immediately assembled around one of these - 7 November – commemorating the birthday of Maria Skłodowska-Curie (7 November 1867). The group decided to propose to IOMP ExCom and to firmly support 7 November as the date for International Day of Medical Physics.

This date has several advantages, among them:
- It was next to the International Day of Radiology, thus allowing in various places medical physicists to celebrate together with their closest medical colleagues – specialist in radiography, radiology and medical imaging;
- It was introducing an excellent patron for the profession - Maria Skłodowska-Curie, what would also attract more young women in the profession
- It was convenient for colleagues from the North as well as from the South hemisphere.

All members of the IOMP ExCom approved 7 November and a number of actions took place. The IDMP Work Group (John Damilakis, William Hendee, Raymond Wu, Simone Kodlulovich Renha, Fridtjof Nusslin) drafted a plan, which was initiated with the creation of a specific area of the IOMP Web site associated with the IDMP [6], plus Facebook and Twitter pages. The preparation of these was headed by Magdalena Stoeva and they were activated early in 2013. Related to these a new IDMP poster was prepared and it was decided each year to have a new poster and new theme.

The IDMP date was announced to all IOMP Regional Organisations and all accepted it. It was also announced in all IOMP Media and was the main topic of the 20th International Conference on Medical Physics (August 2013) in Brighton, UK, co-organised by IOMP, EFOMP and IPEM – the host of this big Conference celebrating the IOMP Golden Anniversary.

The first celebration of IDMP on 7 November 2013 was a great success. It included an address of the then IOMP President (then Dr KY Cheung), what became a tradition for the years to come. The colleagues were celebrating in many countries – some with seminars and conferences, other with rallies through their cities and various other ways. The IOMP special web site and eMPW include annually many photos of these celebrations [7]. Dr Simone Kodlulovich Renha from ALFIM even prepared IDMP T-shirts for the celebrations.

With the time more and more colleagues from all over the world celebrate this day, which provides an excellent opportunity for the visibility of medical physics in healthcare and society at large.

Each IDMP is associated with specific theme and poster. Further down are listed the IDMP themes during the first 10 years of IDMP. Fig. 1 presents the posters during the first 10 IDMPs (2013-2022).

IDMP Themes for each of the first 10 IDMPs

IDMP 2013: Radiation exposure from medical procedures, ask the Medical Physicist!

IDMP 2014: Looking into the Body – Advancement in Imaging through Medical Physics

IDMP 2015: Better Medical Physics = Better Cancer Care in Radiation Oncology

IDMP 2016: Education in Medical Physics – the Key to Success

IDMP 2017: Medical Physics: Providing Holistic Approach to Women Patients and Women Staff Safety in Radiation Medicine (IDMP 2017 celebrates the 150th birthday of Maria Skłodowska-Curie)

IDMP 2018: Medical Physics for Patient Benefit

IDMP 2019: IT'S A MEDICAL PHYSICS WORLD! (IDMP 2019 celebrates the 35th anniversary of MPW)

IDMP 2020: Medical Physicist as a Health Professional

IDMP 2021: Communicating the Role of Medical Physicists to the Public

IDMP 2022: Medical Physics for Sustainable Healthcare

The theme of the IDMP 2023 is associated with the IOMP 60th Anniversary:
IOMP's 60th Anniversary: Standing on the Shoulders of Giants

Fig. 1 IDMP Posters in the first 10 years

III. Further activities, associated with the IDMP

A main objective of the IOMP in the period 2015-2018 was further increasing the visibility of the profession. Due to this reason at the IOMP ExCom meting on 10 June 2015 (at WC2015, Toronto) the then IOMP President Dr Slavik Tabakov and the then IOMP Chair of Awards and Honour Com Dr Simone Kodlulovich Renha proposed a special IDMP Award to be established by IOMP. By the end of the year the documents for this award were prepared and published at the December 2015 issue of eMPW.

The IDMP Award was formed to give recognition to the medical physicist of each IOMP region who has made a significant contribution to promoting Medical Physics, including development of scientific work, improvements in patient care and/or contributions for education and training in medical physics. The IDMP Award was made to be presented on the occasion of the celebration of IDMP to one Medical Physicist from each IOMP Regional Organization (EFOMP, AFOMP, SEAFOMP, MEFOMP, ALFIM, FAMPO and North America), totalizing 7 awards per year. The recipients of the Award was planned to be announced on the day before IDMP (6 Nov).

It was decided the first IDMP Awards (for 2015 and 2016) to be presented at the International Medical Physics Conference in Bangkok (9-12 December 2016). Fig.2 shows the first awarding of the IDMP Awards. This awarding continues since this time. During the first 10 years (2013-2022) 40 colleagues from all IOMP Regional Organisations received the IDMP Award:

2015
Tomas Kron, Australia (AFOMP)
Julio Pinuela, Venezuela (ALFIM)
Anchali Krisanachinda, Thailand (SEAFOMP)
Ibrahim Duhaini, Lebanon (MEFOMP)
2016
Arun Chougule, India (AFOMP)
Sandra Guzman, Peru (ALFIM)
Kwan Ng, Malaysia (SEAFOMP)
Abdalla N. Al-Haj, Saudi Arabia (MEFOMP)
2017
Howell Round, New Zealand (AFOMP)
Diana Feld, Argentina (ALFIM)
Huda M. Al-Naemi, Qatar (MEFOMP)
Virginia Tsapaki, Greece (EFOMP)
Taofeeq Ige, Nigeria (FAMPO)
2018
Hasin Anupama Azhari, Bangladesh (AFOMP)
María Ester Brandan, Mexico (ALFIM)
Jamila Salem Humaid Ali, UAE (MEFOMP)
Renato Padovani, Italy (EFOMP)
Caridad Borrás, USA (AAPM)
Kavuma Awusi, Uganda (FAMPO)
2019
Efi Koutsouveli, Greece (EFOMP)
Eva Bezak, Australia (AFOMP)
Jacob van Dyk, Canada (AAPM)
Hanan Aldousari, Kuwait (MEFOMP)
Moses Adebayo Aweda, Nigeria (FAMPO)
2020
Tae Suk-Suh, S Korea (AFOMP)
Carlos E. Almeida, Brazil (ALFIM)
Oliver Blanck, Germany (EFOMP)
Christoph Trauernicht, S.Africa (FAMPO)
Mohammad Hassan Kharita, Qatar (MEFOMP)
Djarwani S. Soejoko, Indonesia (SEAFOMP)
Robert Jeraj, USA (AAPM)
2021
Stephen Balter, USA (AAPM)
Shigekazu Fukuda, Japan (AFOMP)
Jose Perez Calatayud, Spain (EFOMP)
Michel Salvator Israel, Bulgaria (EFOMP)
Francis Hasford, Ghana (FAMPO)
Mashari Al-nuaimi, KAMP (MEFOMP)
2022
Anchali Krisanachinda, Thailand, (SEAFOMP)
Rabih Hammoud, QaMPS (MEFOMP)
Geoffrey S. Ibbott, USA (AAPM)

The IDMP celebrations quickly transferred from the IOMP to the colleagues in the WHO and the IAEA and on 7 November 2017, at the Asia-Oceania Congress of Medical Physics in Jaipur (4-7 November 2017) IAEA made the first global webcast of the IDMP. The IDMP celebration in 2017 was special as it marked the 150th birthday of Maria Skłodowska-Curie. Due to this reason, it was dedicated to women in medical physics. It is interesting, that following the success of the IDMP, our biomedical engineering colleagues started to celebrate globally in October 2016 the Global Clinical Engineering Day (which in fact was set up as such on 21 October 2006).

Fig.2 First presentation of IDMP Awards, Bangkok, 2016

IV. Conclusion

The International Day of Medical Physics provided excellent global visibility of the profession. Additionally it created opportunities for colleagues to meet more often within their societies, as well as with the their medical colleagues. The success of the IDMP led to establishing in 2020 of an International Medical Physics Week [8], usually including various online seminars on new medical physics topics.

In several countries IDMP celebrations were associated with open days of medical physics, allowing the professional achievements, new medical equipment and associated methods, to be presented to society at large, medical specialists or university colleagues from other professions.

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ANNEX

The Origins of Positron Emission Tomography

Michel M. Ter-Pogossian

The development of positron emission tomography (PET) took place through the combination of the following recognitions: (1) a handful of short-lived, positron-emitting radionuclides, carbon-11, nitrogen-13, and oxygen-15, exhibit chemical properties that render them particularly suitable for the tracing of important physiological pathways, and (2) the radiation emitted as a result of the annihilation of positrons in matter exhibited physical properties that made it well-suited for nuclear medicine imaging, particularly for tomographic reconstruction. The scientific building blocks that were necessary for the structure of PET were contributed over a period of several decades by many investigators in physics, mathematics, chemistry, and fundamental biology.

POSITRON emission tomography (PET) is a nuclear medicine imaging modality that consists of the systemic administration to a subject of a radiopharmaceutical labeled with a positron-emitting radionuclide. Following administration, its distribution in the organ or structure under study is assessed as a function of time and space by (1) detecting the annihilation radiation resulting from the interaction of the positrons with matter, and (2) reconstructing the distribution of the radioactivity from a series of measurements taken at different angles, an approach very similar to that used in computed tomography (CT).

PET exhibits some specific characteristics that identifies it within the broader field of nuclear medicine imaging. The only nuclides used in PET decay by positron emission, and their presence in vivo is always detected through the use of the two annihilation radiation by the coincidence detection of the annihilation photons. These nuclides most generally exhibit chemical properties that render them particularly desirable in physiological studies. The radionuclides most widely used in PET are listed in Table 1. Note that oxygen, carbon, and nitrogen are atoms essential to most physiological processes, and fluorine has been found to be a useful analog in physiological tracing as well as an important marker as an intrinsic marker for fluorine. The images yielded by PET are usually displayed as tomographic sections.

The conceptual structure of PET consists of building blocks that were contributed by scientific investigations. These building blocks were generated during the history of artificial radioactivity, and the maturation process of PET has been slow.

Historically, the development of PET can be divided into three phases: (1) the application in physiological studies in the earlier days of artificial radioactivity of a small number of positron-emitting radionuclides; (2) the recognition that a certain number of short-lived, positron-emitting radionuclides exhibit properties that rendered them particularly useful in nuclear medicine physiological studies in spite of some of their shortcomings; and (3) the combined use of the previously mentioned positron-emitting radionuclides with the coincidence detection of the annihilation radiation and the tomographic reconstruction process from projections. On a time scale, the first period extends between the early 1930s to the late 1940s; the second period between the middle of the 1950s to the early 1970s; and the third period from the end of the second to the present (Fig 1).

FIRST PHASE

Before the discovery of artificial radioactivity, the use of radioactive tracers in biology and medicine was severely limited by the physical and chemical properties of naturally occurring radioelements. In 1934, Irene Curie and Frederic Joliot discovered that when exposed to irradiation by alpha particles emitted by polonium, some nuclides—such as aluminum, boron, and magnesium—emitted a penetrating radiation after the source of alpha rays was removed. The intensity of this penetrating radiation decreased as a function of time. It is interesting to note that nitrogen-13, generated by the nuclear reaction $^{10}B + {}^{4}He = {}^{13}N + {}^{1}n^{1}$, was among the very first artificially produced radionuclides. At the time, the half-life of ^{13}N

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Table 1. The "Physiological" Radionuclides

Nuclide	Approximate Half-Life
^{11}C	20.4 min
^{13}N	10 min
^{15}O	120 s

was measured as approximately 14 minutes. The amount of artificially produced radionuclides was severely limited by the intensity of alpha particle fluxes available from naturally occurring radionuclides. The acceleration of ions by the cyclotron, which was developed at the University of California in Berkeley by Ernest O. Lawrence between 1930 and 1936, provided intense sources of accelerated positive ions, which permitted the generation and study of a very large number of artificially produced radioelements. It is a quirk of scientific investigation that, the cyclotron was developed with the purpose of transmutation of elements with no thought of producing artificial radioactivity, and that the discovery of Irene Curie and Frederic Joliot prompted the Berkeley group to note that the transmutations produced by their apparatus led often to radioactive substances.

The abundant availability of radioactive iso-

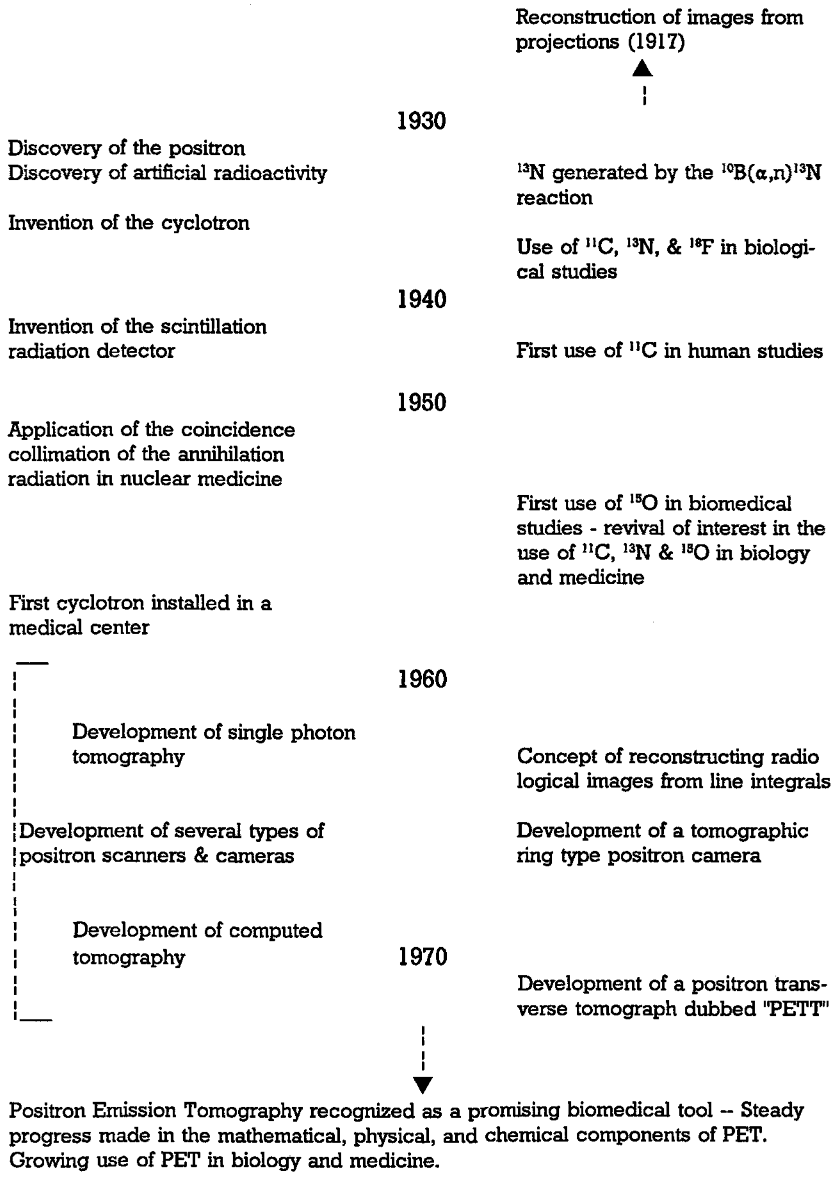

Fig 1. Milestones in the historical development of PET.

topes spread over most of the periodic table stimulated in Berkeley the interest not only in studying these substances but also in using many of them in biological research. In many instances, the interest of these early investigators focused on radionuclides whose physical properties were akin to physiological processes. Several of these radionuclides are those that have provided the foundation for positron emission tomography.

Shortly after the development of the cyclotron in Berkeley, the usefulness of carbon-11, (^{11}C), ^{13}N, and fluorine-18 (^{18}F) as radioactive tracers for biological studies was recognized. In the late 1930s and early 1940s, Kamen[2] used ^{11}C in the study of carbon dioxide use by plants, and Cramer and Kistiakowsky[3] used lactate acid labeled in the 1, 2, and 3 positions for metabolic studies. In the middle 1940s, Buchannan and Hastings[4] used ^{11}C in the study of intermediary metabolism. One of the very early studies, if not the first one, carried out in human subjects by means of ^{11}C was performed by Tobias et al,[5] who used ^{11}C-labeled carbon monoxide to study its activity in man. Ruben et al[6,7] reported on the use of ^{13}N in the study of nitrogen fixation by nonlegumenous plants. Fluorine-18 was used in the early 1940s by Volker et al[8] in the study of the absorption of fluorides by enameled dentine and bone, and by Wills[9] in studying the secretion of intravenously injected fluorine in the submaxillary gland saliva of the cat. In that early period, the investigators most active in using cyclotron-produced, short-lived radionuclides were skeptical of the possible usefulness as radioactive tracers of ^{13}N and oxygen-15 (^{15}O). In *Isotopic Tracers in Biology,*[2] Kamen states "because of its short half-life and because it must be produced by a d,n reaction involving an installation like the cyclotron, N-13 is too restricted in application to be considered of importance as a tracer for nitrogen." In the same reference, "No radioactive isotope of oxygen is sufficiently long-lived to be useful in tracer work." Elsworth C. Dougherty stated in *Isotopic Tracers and Nuclear Irradiations,*[10] "Nitrogen-13 may be made in the cyclotron by the reaction $^{12}C(d,n)^{13}N$ but it is not a promising agent despite excellent cyclotron yields. It has had very limited biological applications as a tracer." And, in the same reference, "The unstable species of longest half-life is oxygen-15 (126 seconds), this has not been employed for tracer work and does not offer much promise." It is clear now that these early assessments were unduly pessimistic.

Between the middle 1940s and the early 1950s, the interest in using ^{11}C, ^{13}N, and ^{18}F in biomedical studies dwindled, perhaps because the discovery of ^{14}C in 1940 by Kamen and Ruben provided a much more flexible label than ^{11}C for tracing organic compounds. Also, because of the availability of reactor-produced radioelements, the focus of in vivo tracer methodology shifted to other labels, particularly iodine-131. For practical purposes, short-lived, cyclotron-produced, positron-emitting radionuclides became inconsequential in biomedical research between the middle 1940s and the middle 1950s, thus ending the first phase of PET.

SECOND PHASE

In the middle 1950s, Ter-Pogossian and Powers[11] rekindled at Washington University an interest in using, in spite of their short half-lives, short-lived radionuclides for physiological studies. The early phase of this work consisted of using radioactive ^{15}O for the study by autoradiography of oxygen tension in malignant neoplasms. This pioneering effort in the use of ^{15}O led to the use of ^{15}O-labeled oxygen and other radioactive gases for respiratory and cerebral metabolic studies.[12] The short-lived radionuclides were generated in a cyclotron installed at Washington University in the early 1940s for the specific purpose of producing medically useful radionuclides. The results of the above investigations were sufficiently promising to lead in the early 1960s to the installation, with National Institutes of Health support, of a cyclotron in the Washington University Medical Center for the generation of short-lived radionuclides for use in in vivo metabolic studies. These early experiments stimulated active work with short-lived, cyclotron-produced radionuclides, particularly gases, at the Hammersmith Hospital in London, where the first cyclotron in a medical center had been commissioned in 1955 for the general purpose of providing radionuclides for nuclear medicine for radiation therapy and radiobiologic studies.

Encouraged by these early results in the decade following the 1960s, the scope of the use of these short-lived physiological radionuclides grew slowly at first. Their use then grew more rapidly in a number of centers, most notably at the Massachusetts General Hospital in Boston and the Sloan Kettering Institute in New York, where small cyclotrons dedicated to the production of short-lived, positron-emitting radionuclides were installed, and at Ohio State University and the University of California at Berkeley, where older, existing cyclotrons were used. Three early studies were of particular importance in the development of this new tool in biomedical research:

1. It was recognized that the majority of metabolic processes fundamentally important to life occur rapidly enough to be traced by means of the short-lived physiological radionuclides listed in Table 1.
2. A number of chemists became interested in the labeling of molecules of physiological importance with the above mentioned short-lived radionuclides. This interest led to the development of a number of rapid labeling procedures suitable for the incorporation of these short-lived labels into radiopharmaceuticals.
3. In the early days of the use of positron-emitting radionuclide labeling of radiopharmaceuticals, the annihilation radiation was considered to be less than optimal for its detection and collimation because of its relatively high energy of approximately 511 keV. However, during the period under discussion, it was demonstrated that the two annihilation photons traveling nearly colinearly offered substantial advantages in the collimation of this radiation.[13,14] This property of the annihilation radiation was found later to be particularly desirable in the tomographic reconstruction of the distribution of positron emitters. It is well recognized now that the annihilation radiation offers substantial advantages over single gamma ray photons for in vivo nuclear medicine imaging.

The advantages of detecting the annihilation radiation by the coincidence method were exploited by several investigators during that period.[14-16] Positron-emitting, short-lived radionuclides were used in a series of physiological studies including pulmonary, cerebral, and hepatic studies. In these early studies the annihilation radiation was detected by means of scanners, multiprobe systems (Fig 2), and cameras (Fig 3)[17-20] designed specifically for the detection of the annihilation radiation. In the early 1960s, Rankowitz et al[21] developed a positron scanner for the localization of brain tumors. The scanner consisted of a ring of scintillation radiation detectors designed for the coincidence collimation of the annihilation radiation. The system provided transverse tomographic sections of the distribution of positron-emitting radionuclides. Although the quality of the images obtained by this system was limited by sampling data and lack of attenuation correction, the design demonstrated the advantages that could be gained from the combined use of electronic collimation and tomographic imaging in mapping the distribution of positron emitters. In 1963, Kuhl and Edwards[22] developed a nuclear medicine tomographic imaging device designed for the imaging of nuclides decaying with the emission of gamma rays. This device, which was the ancestor of modern single photon emission computed tomography systems, clearly demonstrated the usefulness of the tomographic imaging in nuclear medicine. The advantages exhibited by positron-emitting radionuclides for nuclear medicine imaging were analyzed by several authors, including Chesler [23] and Cormack.[24] It became apparent at the time that for tomographic imaging, the annihilation radiation exhibited three major advantages over gamma rays: (1) the coincidence collimation of the annihilation radiation is a more efficient process than the collimation by absorption of gamma rays, (2) the coincidence detection of the annihilation photons allows a very accurate compensation for the attenuation of the radiation in tissues, and (3) the isoresponse curves for the coincidence detection of annihilation photons are nearly uniform.

THIRD PHASE

The numerous scientific investigations carried out before the early 1970s and pertaining to the use of a handful of positron-emitting radionuclides had by that period coalesced into a clearly perceivable pattern: The short-lived,

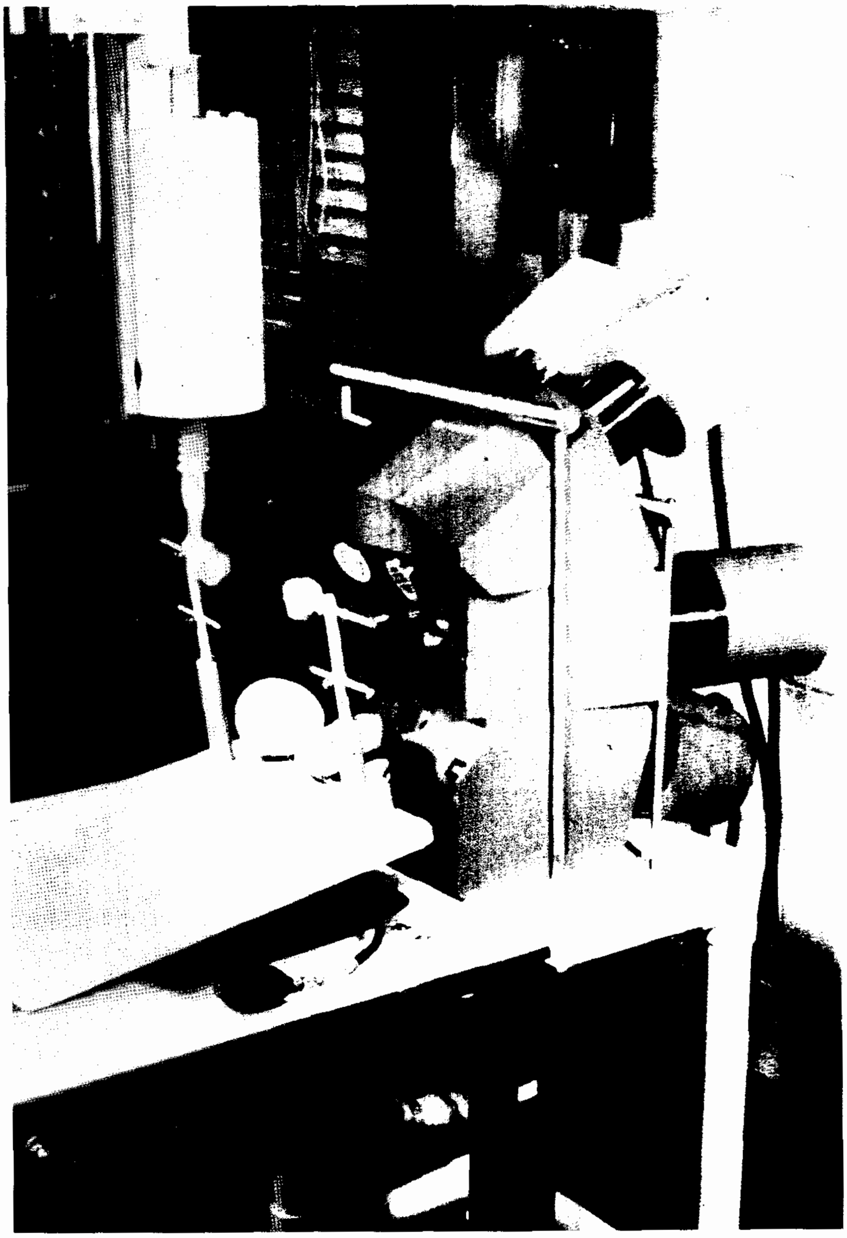

Fig 2. Array of six scintillation detectors fitted with converging collimators for the determination of regional cerebral blood flow and oxygen metabolism by means of ^{15}O.

positron-emitting radionuclides, ^{15}O, ^{11}C, ^{13}N, and ^{18}F, had been found to be useful tracers in physiological studies either difficult or impossible by any other means.[25,26] Oxygen-15, once considered useless as a physiological tracer, had proven to be a useful tracer for that element, which was used extensively, particularly in neurological studies.[27-29] Although short-lived, many of these labels had been incorporated into increasingly complex molecules, and the detection for in vivo studies of the annihilation radiation had been found not only less burdensome than more conventional gamma radiation, but it offered some features, particularly in tomographic imaging, unmatched by the detection of single photons.

In the early 1970s, the research group at Washington University, led by Ter-Pogossian, was faced with the need to develop an imaging device to expand this groups' long interest, since the middle 1950s, in using short-lived "physiological" radionuclides. After investigat-

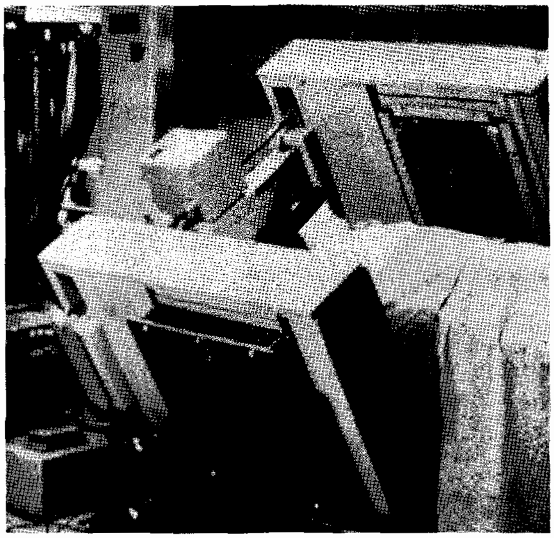

Fig 3. The Massachusetts General Hospital positron camera. (Reprinted courtesy of Gordon L. Brownell and the Physics Research Laboratory at Massachusetts General Hospital.)

ing various possible configurations, this group developed a positron emission transverse tomograph, which was dubbed PETT III.[30] PETT III was a very early version incorporating the fundamental features of modern PET devices. This system used coincidence electronic collimation of the annihilation radiation. The image reconstruction from projections was similar to that used by Hounsfield et al[31] and Cormack[32,33] for transmission CT. The motions in PET were designed to provide the necessary linear and angular samplings dictated by theory for the faithful reconstruction of the image. The attenuation of the annihilation radiation was compensated for by measuring that attenuation for each coincidence line by the use of a ring of positron emission activity. A clinical version of PETT III was used extensively in animal and patient studies at Washington University and later at Brookhaven National Laboratory. The physiological studies carried out with short-lived physiological radionuclides and tomographic reconstruction stimulated much interest in the modality, which by then was widely known as PET. Investigators from different disciplines focused their attention to the technical aspects of PET. Chemists became ambitious in labeling rapidly increasingly complex molecules. In 1980, a list of approximately 30 compounds labeled with short-lived, positron-emitting radionuclides was included in an article published in *Scientific American.*[34] Since that publication the list has increased to several hundred. The encouraging results obtained with the early PET tomographs stimulated the development of a large number of new architectures. These included an adaptation of the Massachusetts General Hospital camera for positron tomography, the use of Anger cameras for the same purpose, and several configurations using different size and numbers of detectors. It should be noted that in the majority of these efforts scintillation counters were used as radiation detectors. Although there has been some investigation of the use of different detectors, particularly multiwire proportional counters, so far only scintillation detectors have been found to be useful in PET physiological studies. In the same period, much effort was expended in understanding the mathematical aspects of PET image reconstruction, and several different reconstruction algorithms have been tested with increasing degrees of success. Perhaps most important in the development of PET was the general recognition by the biomedical community of the usefulness of this technique in the in vivo study of regional biochemical processes essential to life. An important facet of these physiological studies was the well-accepted recognition that the proper use of the data produced provided by PET requires its incorporation into a mathematical model derived, in most instances, from the known biochemistry of some of the pathways of the phenomenon under study.

This third phase in the development of PET can be regarded as the maturation of a new methodology during which the quality of the methodology was and is being continuously improved, while its usefulness is widely accepted.

The analysis of the historical development of PET reveals some interesting characteristics of that methodology. PET owes most of its strength to a serendipitous combination of physical and chemical properties. Had it not been for the chemical properties of the physiological radionuclides, it is probable that positron-emitting radionuclides would have played a minor role in nuclear medicine. Had these physiological radionuclides decayed through the emission of single photon gamma rays rather than positrons, their collimation would have less inefficiency, and the tomographic reconstruction of their distribution would not have yielded the quantitative results and high contrast spatial and temporal resolution that has so enhanced the value of PET. The development of PET was entirely dependent on the separate developments of scientific concepts that in their early stages were pursued without any thought of their combined use. Thus, the application in biomedical research of physiological radionuclides was carried out for over two decades before the early 1970s without any thought of their imaging by a reconstructive tomographic process. The early work carried out in the coincidence detection of annihilation photons focused on the physical properties of this approach rather than on the desire to exploit the chemical properties of some positron-emitting radionuclides. The tomographic reconstruction from projections was developed with little thought to the chemical properties of short-lived, positron-emitting radionuclides or to the desirable features of the coincidence detection of the annihilation radiation. The development of PET consisted in bringing together the above properties and creating a new system using the desirable features of the all the components. Although it is not easy to identify which of the above components contributed most to the usefulness of PET as a biomedical tool, it is probable that the desirable chemical properties of a handful of positron-emitting radionuclides was the most important single concept in the birth of PET.

PRESENT STATUS AND PREDICTABLE FUTURE FOR PET

The development of PET to its present status as a useful research and clinical modality took much longer than the span of the same process of maturation for other imaging modalities such as magnetic resonance imaging (MRI) and CT. This slow acceptance of PET by the scientific community is due in major part to that facts that (1) PET evolved, as pointed out previously, from different disciplines, each contributing its development process, and (2) in most instances, PET requires the presence of a cyclotron and, often, complex chemistry in its operation. The latter factor has slowed down considerably the development of PET, and even today it represents a formidable barrier in its dissemination either for research or in clinical practice.

In spite of the long and difficult "gestation" period, PET has reached a level of maturity where its present position in science can be easily assessed, and its near future can be predicted with some degree of confidence. Today, the PET armamentarium can be regarded as mature technology. Several commercial companies offer cyclotrons specifically designed for PET studies that are relatively easy to operate, reliable, and competitively priced. Extensive progress has been made in the past two decades in developing practical labeling methods for PET radiopharmaceuticals. A number of automated systems, either single-purpose "black boxes" or programmable, robot-based systems, have been developed for the labeling of the most widely used radiopharmaceuticals. Highly advanced PET imaging devices providing good spatial resolution, ease of operation, and tolerable reliability are offered by several major companies.

The scientific literature dealing with PET-related research and applications clearly shows that PET provides a tool that allows us to probe physiological processes essential to life by means unavailable with any other technology. PET has also been found to be highly useful clinically in a series of determinations covering a large number of organs and diseases (Table 2). Although at this time there are less than 100 PET centers in the world, the number of publications in the nuclear medicine literature directly related to PET represents over 10% of the published articles in the nuclear medicine literature.

It is easy and safe to predict that in the near future the PET armamentarium will incrementally improve. Indeed, in addition to cyclotrons, which at this time are the preferred mode for the generation of PET radionuclides, several companies are working on the development of less expensive and easier-to-install accelerators (Fig 4). The performance of the apparatus needed for the labeling of PET radiopharmaceuticals is rapidly improving, and it is quite probable that many of the difficulties encountered with present systems will be overcome in the

Table 2. Some Clinical PET Applications (Established and Potential)

Application	Radiopharmaceutical	Description
Neurology/neurosurgery/psychiatry		
Dementia (Alzheimer's disease)	^{18}FDG, labeled $^{15}O_2$, $H_2{}^{15}O$	Display of areas of decreased activity
Epilepsy	^{18}FDG	Presurgery, replaces depth electrodes
Stroke	^{18}FDG, labeled $^{15}O_2$, $H_2{}^{15}O$	Display of decreased blood flow, tissue damage
Huntington's chorea	^{18}FDG, ^{11}C-N-methylspiperone	Diagnosis
Schizophrenia	^{18}FDG and other pharmaceuticals	Develop biochemical disease definition
Brain receptors	Multiple radiopharmaceuticals, [^{18}F]spiperone	Trace chemistry of brain receptors
Cardiology		
Myocardium viability	^{82}Rb, [^{13}N]ammonia, ^{18}FDG, [^{11}C]acetate	Determination of tissue viability before surgery
Stenosis/restenosis	[^{13}N]ammonia, ^{82}Rb	Early detection of occlusion-evaluation of postrevascularization
Early evaluation of high-risk patients	[^{13}N]ammonia, ^{82}Rb, ^{18}FDG, [^{11}C]acetate	Early detection of CAD-determinative test
Oncology		
Tumor evaluation	^{18}FDG, labeled $^{15}O_2$, $H_2{}^{15}O$, ^{82}Rb, among others	Distinguishes recurrence from necrosis *grading*
Tumor staging	^{18}FDG, labeled $^{15}O_2$, $H_2{}^{15}O$, and others	Dose uptake analysis allows real-time *staging*
Assessment of tumor extent	[^{18}F]estradiol	Identification of EP nodes and metastases

Abbreviations: FDG, fluorodeoxyglucose; H, hydrogen; Rb, rubidium; CAD, coronary artery disease; EP, xx.

near future. The present PET imaging devices provide images with a spatial resolution of approximately 5 mm. It has already been shown that much higher resolutions are possible,[34] and it is probable that the resolution of commercial PET devices also will be improved in the very near future. Perhaps what is particularly important in PET instrumentation is an improvement in sensitivity. Considerable efforts are presently being expanded to increase the solid angle of radiation acceptance of present PET devices. It is easy to predict considerable improvements in that area because the preliminary results obtained are highly encouraging. Industrial companies with suitable competence are becoming more interested in providing PET radiopharmaceuticals with a half-life sufficiently long (usually labeled with ^{18}F) to allow their shipment from a remote site of preparation to a hospital where they are to be used. Also, there is much work to be carried out in developing generator-produced radionuclides so as to minimize the need of on-site generation and labeling of PET pharmaceuticals.

As shown in Table 2, PET has been used for clinical applications as well as for research

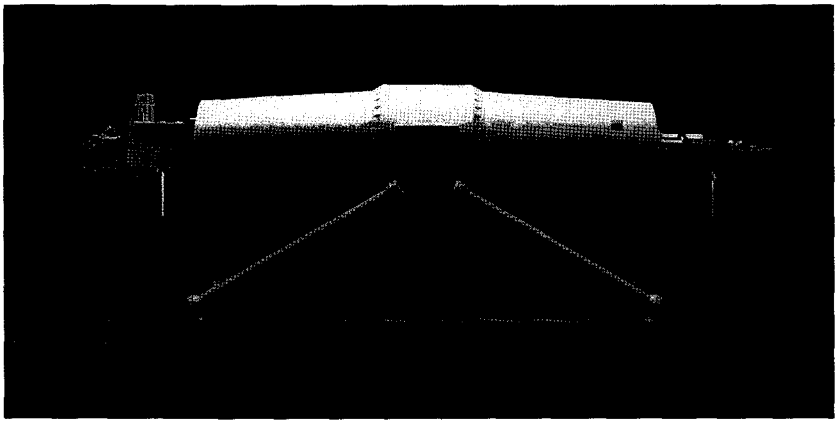

Fig 4. The 3.7-MeV Tandem Cascade Accelerator for PET. (*Reprinted courtesy of Science Research Laboratory and Accelerator Applications Incorporated, Somerville, MA.*)

purposes in a very broad spectrum of applications, and it will probably will continue to do so. Two areas, oncology and psychiatry, offer particularly challenging areas of development for PET. In oncology, PET has already been found to be useful in assessing the viability of tumors engaging the effect of therapy, be it radiation, chemical, or hormonal, in identifying the presence of metastases and in determining their receptor status. There are strong indications that the applications of PET in oncology will develop at a particularly fast rate. Another most promising possible use of PET is in the study of mental disease. Although a certain number of studies have already been carried out, these applications, at this time, are in their infancy, but they offer particularly exciting future possibilities because of PET's unmatched ability to trace in vivo and noninvasively some of the biochemical processes essential to cerebral function.

In closing, it might be useful to compare PET with other medical imaging procedures, such as CT, MRI, and magnetic resonance spectroscopy. It is unquestionable today that CT and MRI are clinically much more important tools than PET, perhaps with the exception of some specific cases in which PET provides information totally unavailable by CT or MRI. It is difficult to comment about the place of magnetic resonance spectroscopy because this modality is still in its infancy, and its future is difficult to predict. PET provides the ability to measure, in vivo, regionally, and noninvasively, a large number of physiological variables that are essential to normal organ functions because pathology derives from or affects normal physiological activities. At this time it appears that PET will contribute to clinical medicine through a better understanding of pathophysiology, and in some applications it will be used directly as a clinical diagnostic tool.

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POSITRON SCANNER FOR LOCATING BRAIN TUMORS*

BNL 6041

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Summary

A system will be described which makes use of positron emitting isotopes for locating brain tumors based on the method developed by Sweet, Brownell and Aranow.[1,2,3] This system inherently provides more information about the distribution of radioactivity in the head in less time than existing scanners which use one or two detectors. A stationary circular array of 32 scintillation detectors scans a horizontal layer of the head from many directions simultaneously. The data, consisting of the number of counts in all possible coincidence pairs, is coded and stored in the memory of a Two-Dimensional Pulse-Height Analyzer.[4] A unique method of displaying and interpreting the data will be described which enables rapid approximate analysis of complex source distribution patterns.

Introduction

For a number of compounds, the rate of uptake by brain tissue is slower than the rate of uptake by muscle tissue or by certain types of tumor tissue. Thus, after intravenous injection of labeled compounds, the radioactivity may be higher temporarily in brain tumors than in surrounding healthy brain tissue. This phenomenon has been used to locate tumors in the head. The technique is difficult because the tracer level in the blood stream and in muscle tissue is comparable to that in the tumors; the activity ratios are small and the effect is transitory. The scanning has heretofore been done with one or two detectors so that it has taken a long time to accumulate data even when relatively large amounts of tracer have been injected.

Sweet, Brownell and Aranow[1,2,3] have used positron emitters as the radioactive tracers. An emitted positron gives rise, through an annihilation reaction, to two 0.51 Mev gamma rays which are emitted in opposite directions. When detectors are placed on opposing sides of the source, a coincidence indicates activity within the cylindrical space connecting the detectors. This has several advantages compared with the use of a single gamma collimated detector, e.g. improved resolution and insensitivity to background single gamma radiation without the necessity of large, heavy shielding and collimating structures. The current work is an extension of this technique, making use of a multiplicity of detectors. This report covers four aspects of this development: 1) factors affecting arrangement of detectors, 2) electronic circuits for counting coincidences, 3) relating output data to activity distribution in the source, 4) preliminary results. The instrument is built and has been tested with artificially produced radiation patterns. It has yet to be tried on human patients, and the best method of analyzing and presenting the data has not been determined.

Arrangement of Detectors

Positron coincidence scanning with two detectors is illustrated in Fig. 1. The detector pair is scanned slowly up and down and forward and back registering the coincidence counts produced by positron annihilation gamma rays on a projection map of the head. A serious disadvantage of this kind of projection representation, also used with the single gamma scanning technique, is the distortion of the recorded radioactivity pattern which can result. In cases of

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m ltiple tumors, the projections can be misl ading even when two projections from different angles are taken.

Additional detectors are desirable to provide more information about the radioactivity pattern with greater speed, i.e. by simultaneously scanning from many directions. One possible configuration is shown in Fig. 2 with the detectors arranged in two planes on each side of the head. The number of coincidences equals $\left(\frac{n}{2}\right)^2$, where n is the total number of detectors. This arrangement is more sensitive to counts at the center of the pattern than at the top and bottom, and some of the detectors are farther from the center than others. It was finally decided to arrange the detectors in a circle as shown in Fig. 3. The system has 32 detectors with 1 1/4 inch diameter by 1 inch deep NaI crystals arranged in a 15 inch diameter circle. Figure 3 shows the sensitive areas which intersect the head, for the coincidences between detector No. 1 and the opposing detectors. The head is, therefore, "scanned" simultaneously from each detector resulting in 9 to 11 paths through the head producing coincidences for each detector. An average head will produce about 170 to 180 coincidence combinations. This ring will take data in one plane and will be moved in 10 steps along the vertical axis of the head to obtain three-dimensional data.

Coincidence Pair Counting System

In addition to the detector counting assembly the system includes: 1) coincidence circuitry which counts coincident pulses between any pair of detectors and codes the data in a form suitable for storage in 2) a Two-Dimensional Pulse Height Analyzer memory.[4]

The detectors are numbered from 1 to 32 sequentially around the circumference. The coincidence counting system, using standard Computer Control Co. "S-Pacs"[5] and compatible laboratory-built circuitry, examines each event, rejecting single counts and multiple coincident counts of three or greater, and finally codes the two detectors in the pair for memory storage. The lower number detector is coded in a train of pulses equal to its assigned number and stored in the X memory of the Two-Dimensional Analyzer. The higher number detector is simultaneously coded into another pulse train equal to its assigned number and stored in the Y memory.

Referring to the system block diagram (Fig. 4), each of the 32 detector amplifier outputs drives one input of a 2 input NAND circuit which in turn sets one stage of the 32 stage shift register. The other input is a gate common to all 32 input NANDS which can prevent setting of the shift register during analysis of an event.

When the input gate is open, any single or multiple coincident event(A) can set the appropriate shift register stages in parallel. The Clock Gate Flip-Flop(B) is set by the switching of any shift register stage through the 32 fold "OR" circuit. The input NAND gate closes immediately(R) preventing acceptance of any more detector pulses until completion of the analysis. The Clock Gate Flip-Flop triggers Pulse Shaper(C) which inhibits for 10μsec the start of the gate(F) to the Clock Multivibrator(G). During this delay period, the states of all 32 stages of shift register are examined in parallel to determine whether the event was a single or a multiple coincidence. Since only the coincidence pair of 0.51 Mev annihilation gammas is of interest in this scan, the analysis of singles and all other multiple coincidences are prevented. The three standardized outputs from the coincidence analyzer, indicating the number of switched shift register stages, are converted in the logic NAND-NOR circuitry to a standard one or zero level voltage(D); logic zero (0 volt represents a coincidence pair, and logic one (-6 volts) represents a single or triple or gher order coincidence. This voltage is gated in a 2 input NAND by a standard 0.6 μsec pulse(E) at the end of the 10 μsec clock gate inhibit pulse. A coincidence pair will result in a closed gate. Any other condition opens the gate and permits the pulse(E) to trigger a delay multivibrator which generates a 10 μsec pulse(L) to reset the shift register, all flip-flops, and open the input gate.

The coding of the 2 detectors involved in a coincident pair proceeds by gating "ON" the free-running Clock Multivibrator after the 10 μsec logic delay period. Shift pulses(G) are generated at about 600 kc. These shift pulses appear simultaneously at the X and Y outputs until the X Gate Scale-of-two is set(K). A 0.6 μsec delay in triggering this scaler permits the last X pulse to appear at M. The number of shift pulses required to change the state of the No. 1 shift register equals the lower detector number involved in the coincidence pair. The No. 1 shift register stage(H) gates through a clock pulse(I) to trigger the X Gate Scale of 2. The shift pulses appear simultaneously at the X and Y outputs until the X Gate scaler is set, inhibiting the X output. The shift pulses continue until the No. 1 shift register stage again gates through a second clock pulse to trigger the X Gate Scaler, resetting it. Returning the scaler to its reset state resets the Clock Gate Flip-Flop and stops the clock. Therefore, the number of pulses in the Y train corresponds to the second detector number involved in the coincidence pair. Resetting the Clock Gate Flip-Flop triggers pulse shaping circuits; one(L) resets the shift register, and a second one generates a "STORE" pulse(P) to the Two-Dimensional Pulse-Height Analyzer Memory.

The "STORE" pulse transfers the X and Y register counts in the Pulse-Height Analyzer into the proper location of its magnetic drum memory. During this memory storage time, the Scanner input NAND's remain blocked(R). As a safety measure, to prevent opening the input gates for the few microseconds between resetting the Clock Gate Flip-Flop and starting the "Dead Time" pulse, the 10 μsec shift register reset pulse is applied to NOR(R). Upon completion of the "Dead Time" pulse the Scanner is able to accept a new input from the detectors.

Data Presentation and Analysis

The stored data in the Two-Dimensional Analyzer consisting of the number of coincident counts recorded in each pair of detectors, sorted into X (horizontal) and Y (vertical) coordinates, can be displayed on the analyzer oscilloscope as an intensity modulated two-dimensional map or as count magnitude curves of the X channels for any selected Y. The curves of any selected group of Y channels may be simultaneously displayed vertically displaced.

The most useful presentation for analyzing the data and locating the tumor is the X-Y map. The curves are used to determine amplitudes and channel groupings more accurately in doubtful regions, when necessary. The display map intensity modulation can be varied with the scale factor switch in binary steps to permit setting the threshold of visibility at different levels.

Although actual tumors behave as extended sources of radiation in an absorbing medium containing varying amounts of lower level radiation, the technique of locating tumors may be illustrated by first observing the coincidence data patterns produced by a point source. Refer to Fig. 5.

1. <u>Point source in center</u>: It is obvious that a point source in the center of the detector circle will produce an equal number of coincident counts in all opposite detector pairs. Since the opposite pairs are 16 detectors apart, the coincidence pattern will be a straight line of constant difference, Y-X = 16, plotted on Fig. 6 as curve 1.

2. Point source 1.5 inches from center on diameter 9-25: If all coincidences are plotted on X-Y coordinates, Curve 2 results. This curve intersects Curve 1, the line of constant differences at only one point, X = 9, Y = 25. Curve 3 results from the source at 3 inches from center on the same diameter. For both curves:

if $X < 9$, $(Y-X) < 16$

and $X > 9$, $(Y-X) > 16$

The diameter on which the source is located is determined therefore by locating the counter pair for which Y-X = 16. The distance of the source from the center of the circle may be determined by observing the coordinates X, Y at which (Y-X) differs most from 16. The location of a point source in the scanned area is then determined by the intersection of the radial line for (Y-X) = 16 and a line defined by any pair of coincidence detectors obtained from the coincidence curve. The coincidence curve as shown here appears on the display scope of the Two-Dimensional Analyzer.

The X,Y coincidence data provides a great deal of information about the location and size and shape of the tumor. A point source can clearly be accurately located. An extended tumor can be located by a similar analysis as long as the background level caused by radiation from surrounding brain tissue and blood is low enough to produce a contrast. A tumor of finite extent will produce a band on the display similar to that from a point source (Fig. 7) whose width is approximately proportional to the average diameter of the tumor. This band will intersect the reference curve Y-X = 16 over some region of coordinates. The center of this intersection will determine the angle of the tumor from the center of the head, and the boundaries can be resolved by observing the outer coordinates along the band and plotting these coincidence lines between the detectors.

The following figures (8a to e) are Polaroid photographs of the Two-Dimensional Analyzer map display for some artificially produced patterns of radioactivity. Each figure contains three photographs of the same display, but with count scales of 2^7, 2^8, 2^9. The positron emitting isotope used as the source of tumor and background radiation is Na^{22}.

Figure (8a) shows the map display for three small (1/4 inch diameter) sources located on the diameter between detectors 9 and 25 at the center and at distances of 3 inches on either side of center with no background radiation. These correspond to curves plotted in Fig. 6.

The straight line, Y-X = 1, which appears on all photographs for the low count scale results from coincidences between adjacent detectors caused by the high energy single gammas emitted by Na^{22} and the proximity of the detectors. This well defined straight line, together with the zero axes, outlines the useful data area of the display. These coincidences are not useful analytically since they tell nothing about the source distribution.

It should be noted that data for Y = 32 does not appear on these photographs because of the selection of display scales available.

Figure (8b) shows the map display for the same 1/4 inch diameter source in the center and a larger source (about 1 1/2 inches diameter) located 2 1/4 inches from center toward detector 9 on the same diameter as in Fig. (8a), with no background.

Figure (8c) shows the same conditions as Fig. (8b) but with a uniform background radiation throughout the head area.

Figure (8d) shows the same conditions as Fig. (8c), but with a third 1/4 inch diameter source (about 1/3 the intensity of the larger one), located on a diameter from 1 to 17 (front to back midline of head), at a distance of 3 inches from center toward detector 1. The curve for this source intersects the reference constant difference line at the XY coordinates 1, 17. Since it is less active than the larger source, it is not visible on the highest count scale.

Figure (8e) illustrates the kind of deductions that can be made about the shape as well as location of the tumor. Four Polaroid photographs of the coincidence data produced by an approximately elliptical tumor between the center and point 3 of Fig. 5 with scale ranges of 2^7 through 2^{10} are shown in a uniform background. One edge of the band of X-Y data coincides with the straight line Y-X = 16, indicating on which side of center the source is located. The band crosses the reference line at (X, Y = 9, 25) indicating the major axis. Since the width of the band is definitely smallest in the region of (X, Y = 9, 25), the source dimension perpendicular to this diameter is smaller than the dimension along the diameter. The width of the X-Y data band at the extremes indicates the approximate length of the source along the diameter (9, 25); the number of coincident pairs in the region of (9, 25) indicates the dimension perpendicular to this diameter.

Thus, by examining the characteristics of the coincidence data on the intensity modulated X-Y coordinate map, a great deal of information about the location, size and shape of the source of radioactivity can be readily obtained despite a high level of background.

A study program is being conducted to determine whether a mathematical solution of the problem of converting the coincidence data to a map of the radioactivity distribution with reasonable errors is feasible. One such method treats each of the N areas within the head (where N equals number of coincidence combinations caused by the radioactivity within the head) as though it were the component of an N dimensional vector. The mapping from the space of such vectors on to the space of coincidence counts is linear and consequently can be represented by a N x N matrix. If this matrix has a stable inverse it is then possible to convert the coincidence data unambiguously to a map of the radioactivity distribution using a simple computer program. The inverse operation is degraded by statistical and system variations in the coincidence counts. It is too soon to tell whether this mathematical approach will prove to be practical. It is also possible that other modes of display may be advantageous.

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Figure Captions

1. Positron coincidence scanning with two detectors

2. Positron coincidence scanning with detectors arranged in two planes on each side of the head

3. Positron coincidence scanning with 32 detectors arranged in a circle

4. Block diagram of coincidence detector pair coding system

5. Positions of test sources for Figs. 6 and 7

6. X-Y coincidence patterns derived from point sources at positions 1 through 5 on Fig. 5

7. X-Y coincidence pattern for point source at center (1) and for 1.5 inch diameter source located between points 2 and 3 on Fig. 5

8a-e. Photographs of Two-Dimensional Analyzer map display. Count scales (top to bottom) are 2^7, 2^8, 2^9. Point source used is 1/4 inch diameter

(a) Three point sources located on diameter between detectors 9 and 25, at points 1, 3 and 5 of Fig. 5

(b) Point source at 1 and larger source between points 2 and 3 of Fig. 5

(c) Same as (b) but with uniform head background

(d) Same as (c) but with third source (point) located three inches toward front of head on front to back centerline

(e) Point source at 1, and approximately elliptical shaped uniform source in field of uniform head background; long axis of source is on 9, 25 diameter. Fourth photo taken with 2^{10} counts full scale.

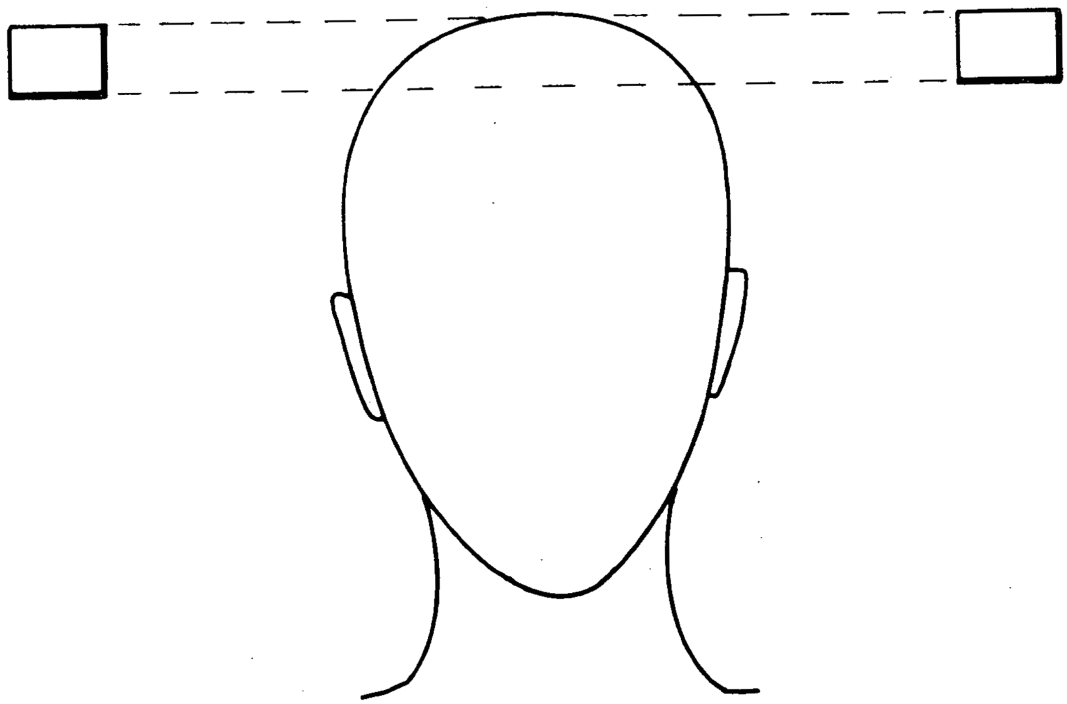

FIG. 1

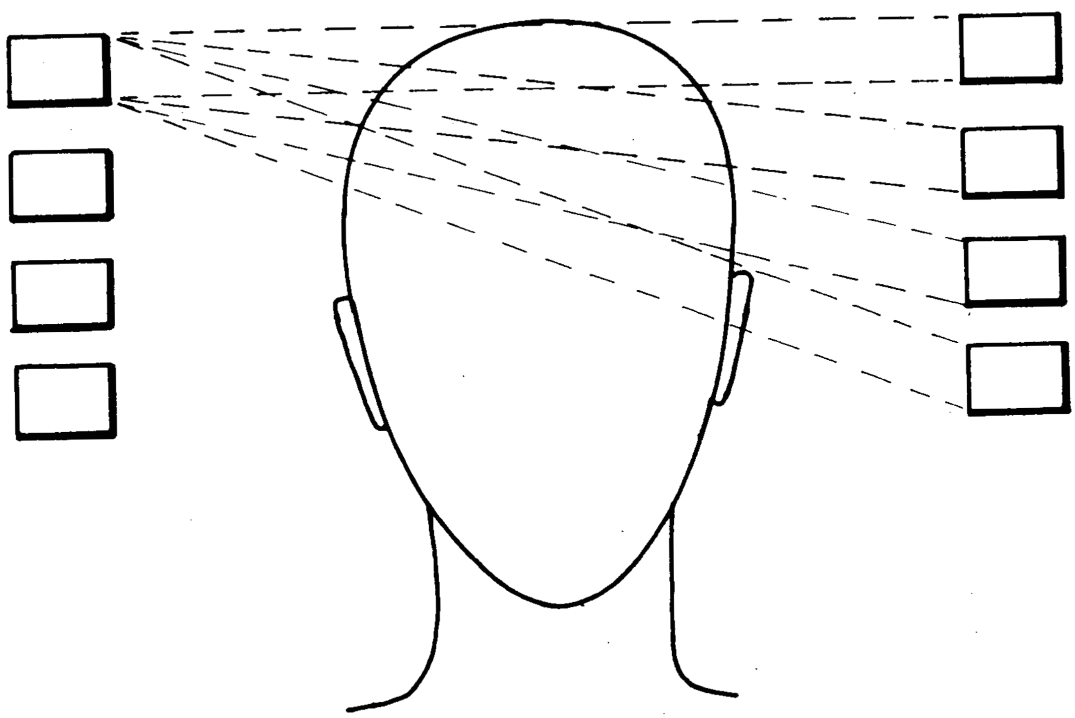

FIG. 2

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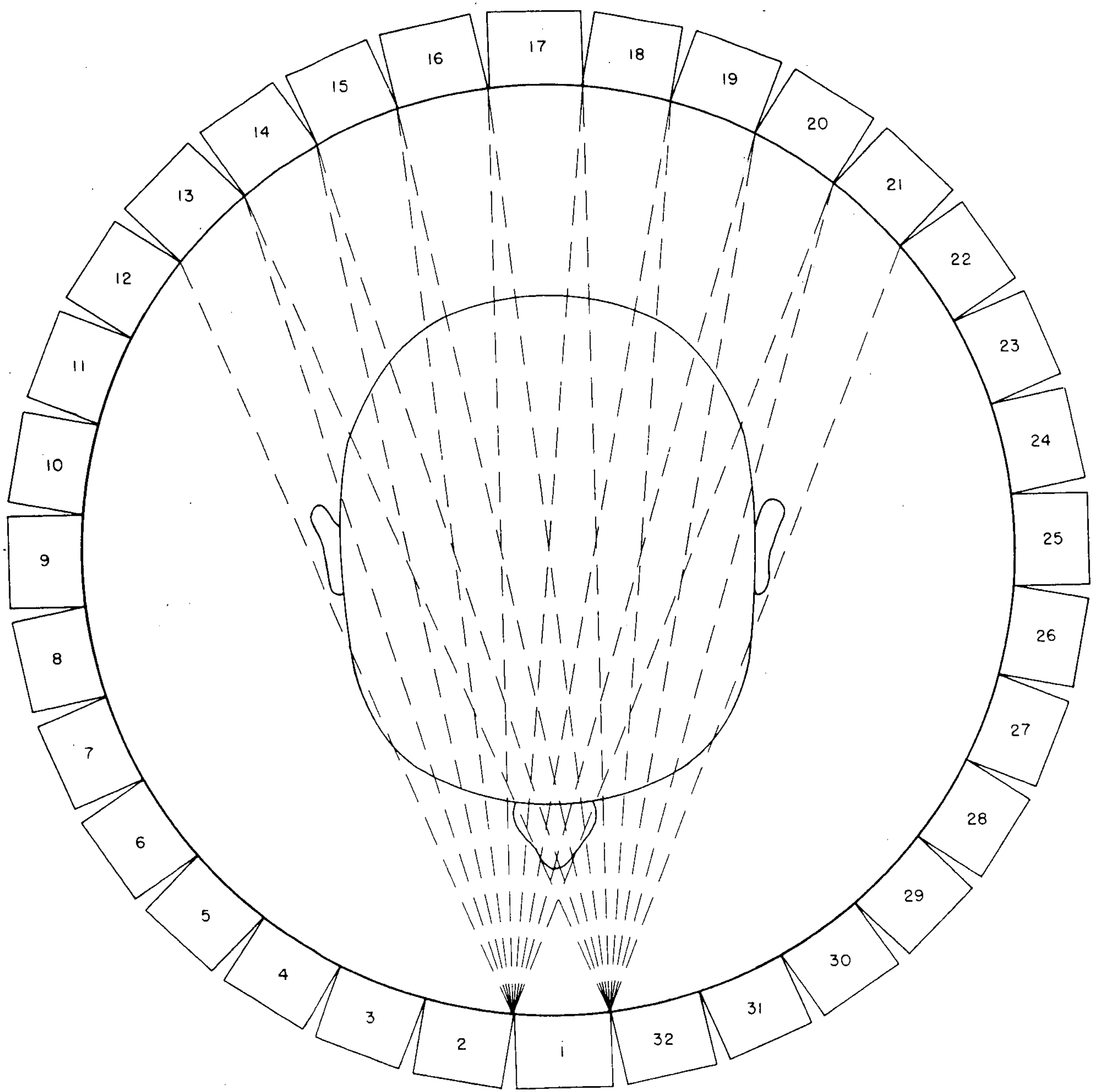

Fig 3

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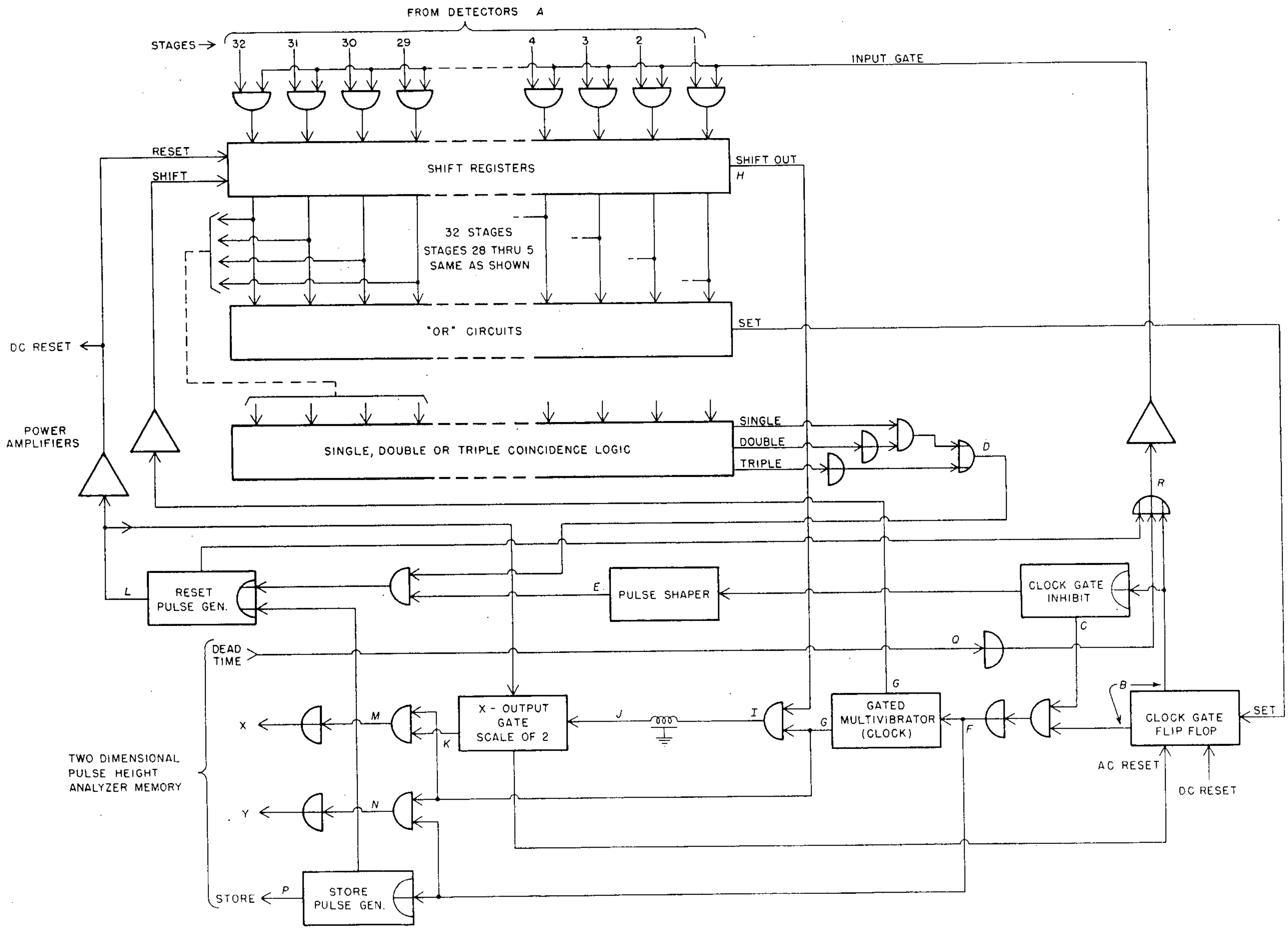

Fig 4

BNL Neg. No. 3-376-62

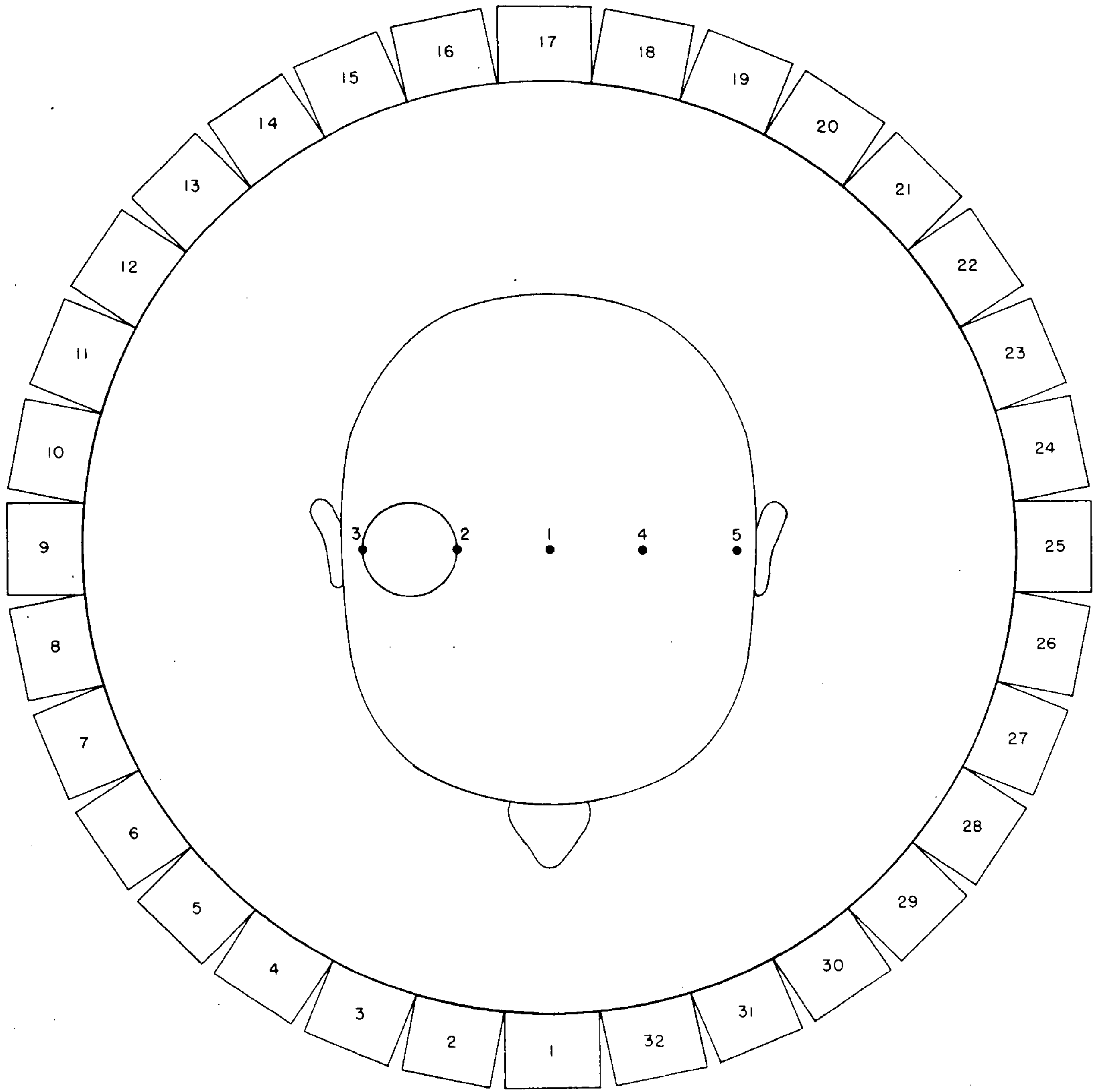

Fig 5
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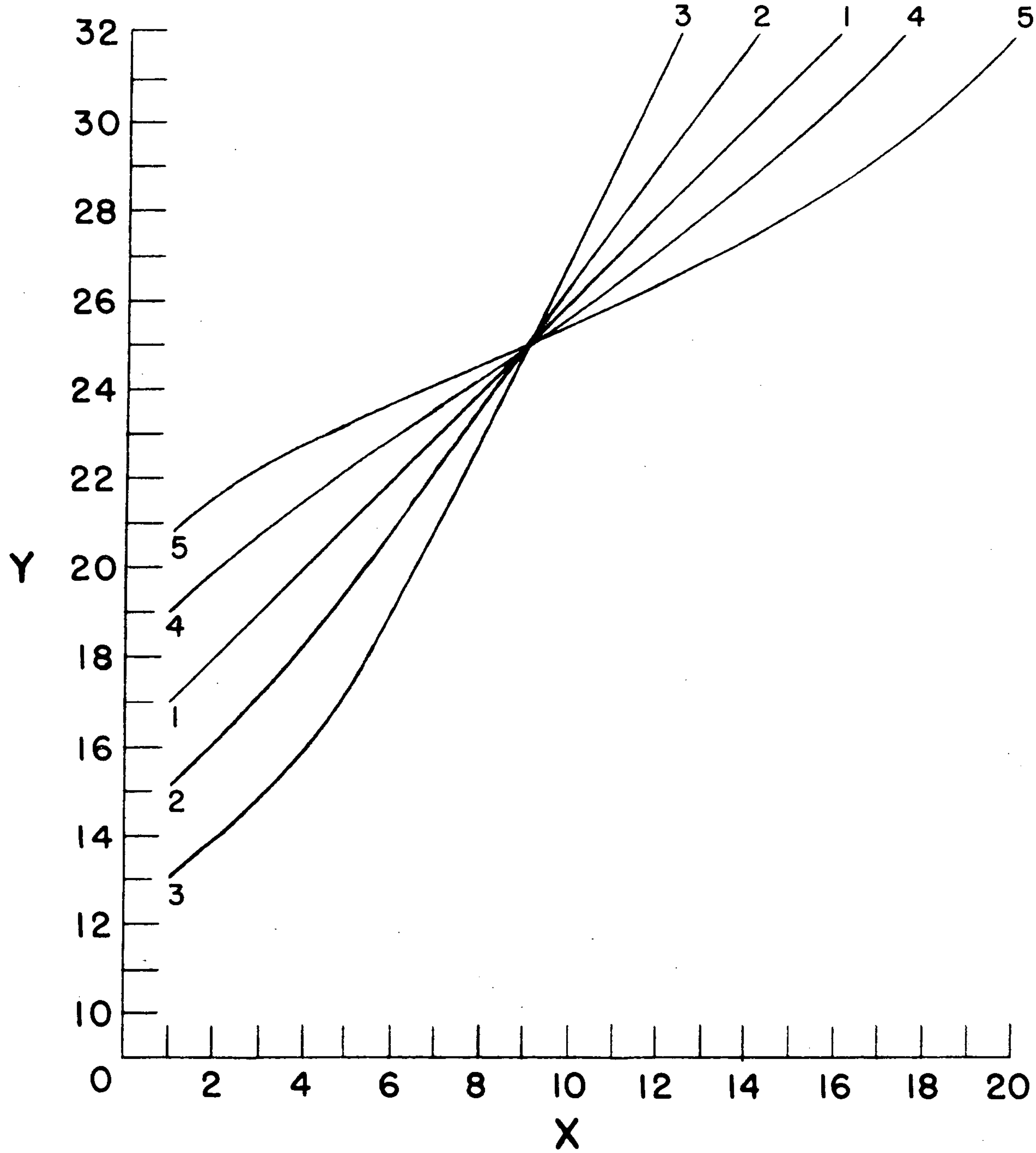

Fig 6

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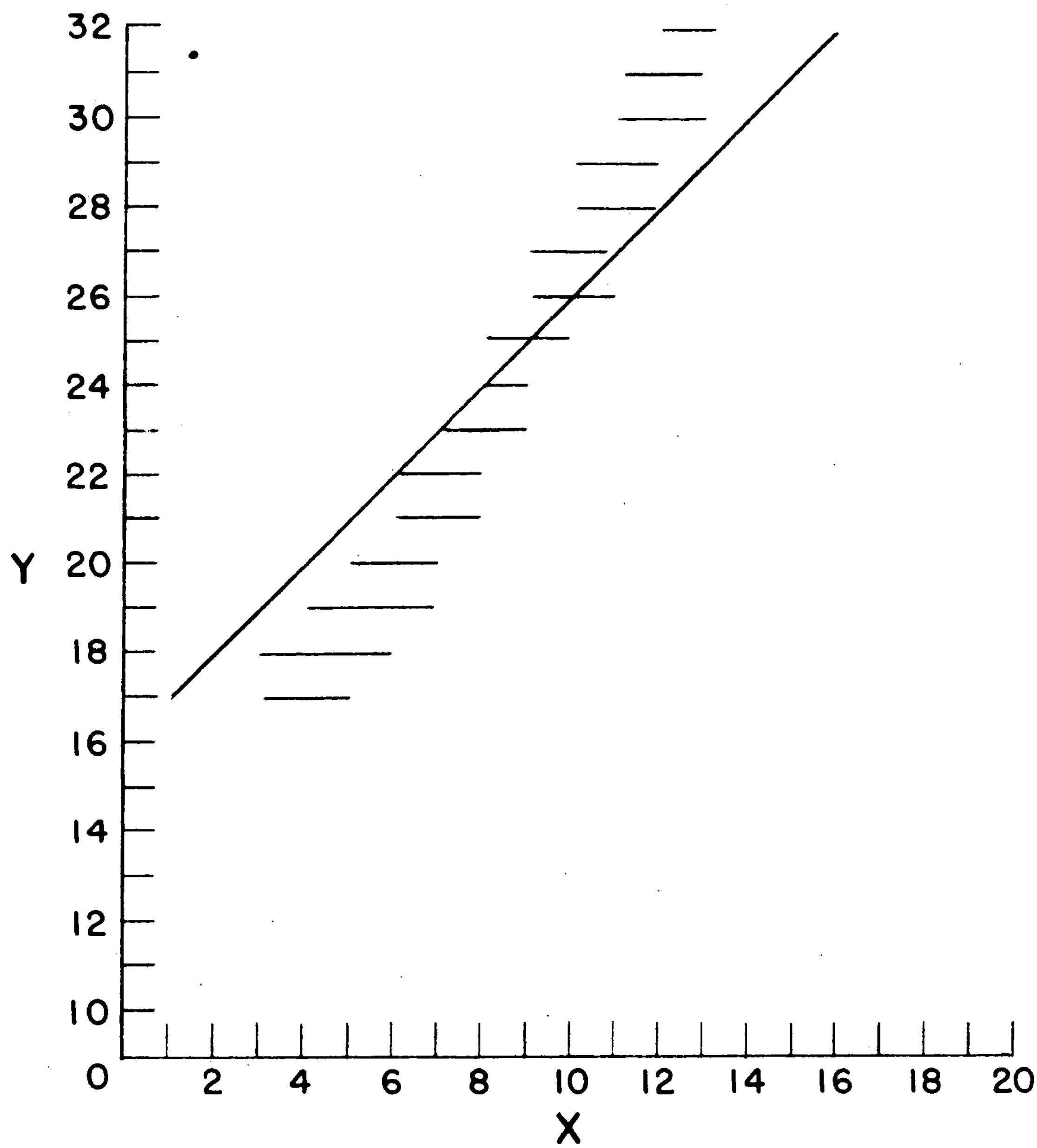

Fig 7
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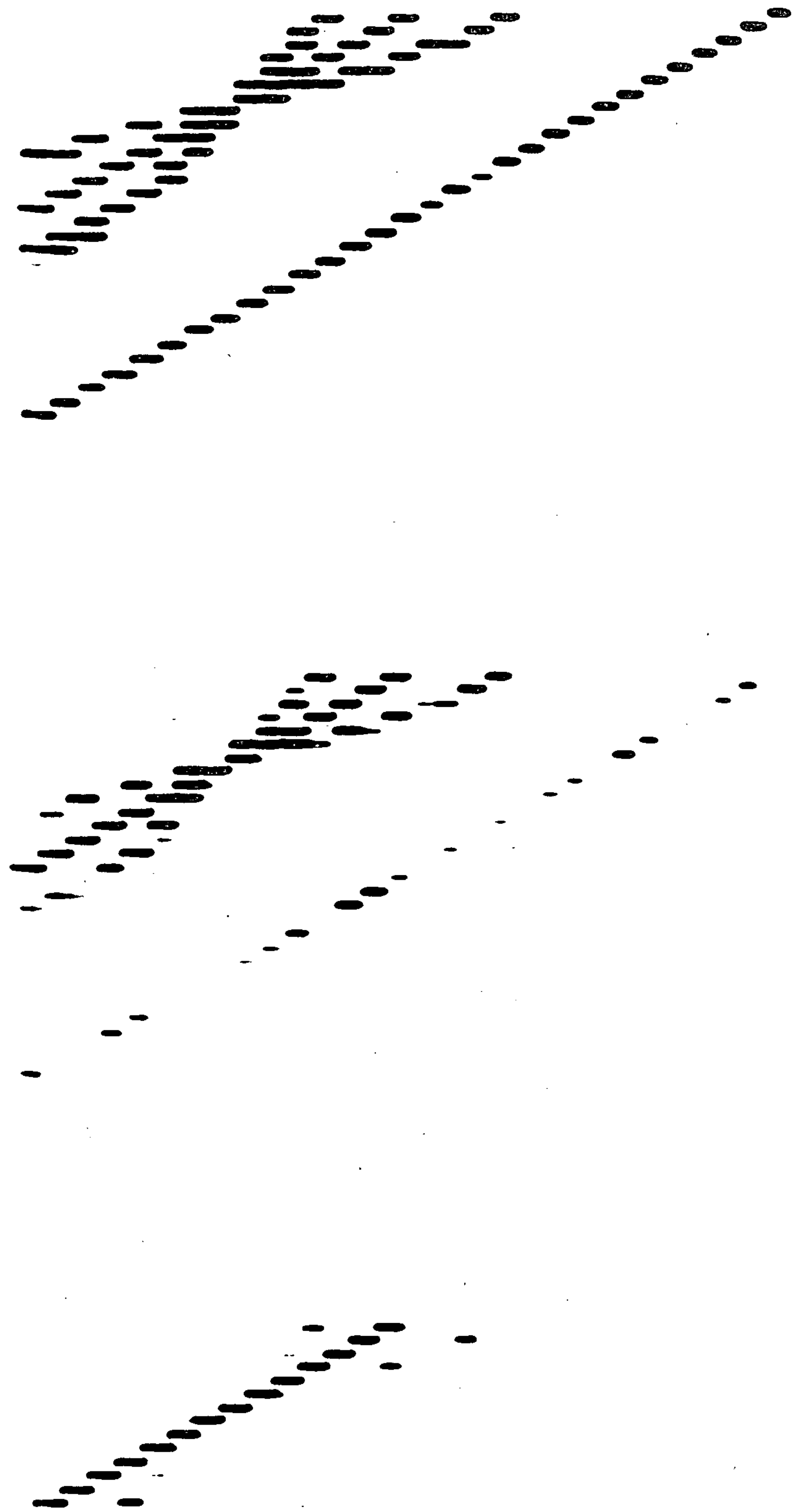

Fig 8a

BNL Neg. No. 3-657-62.

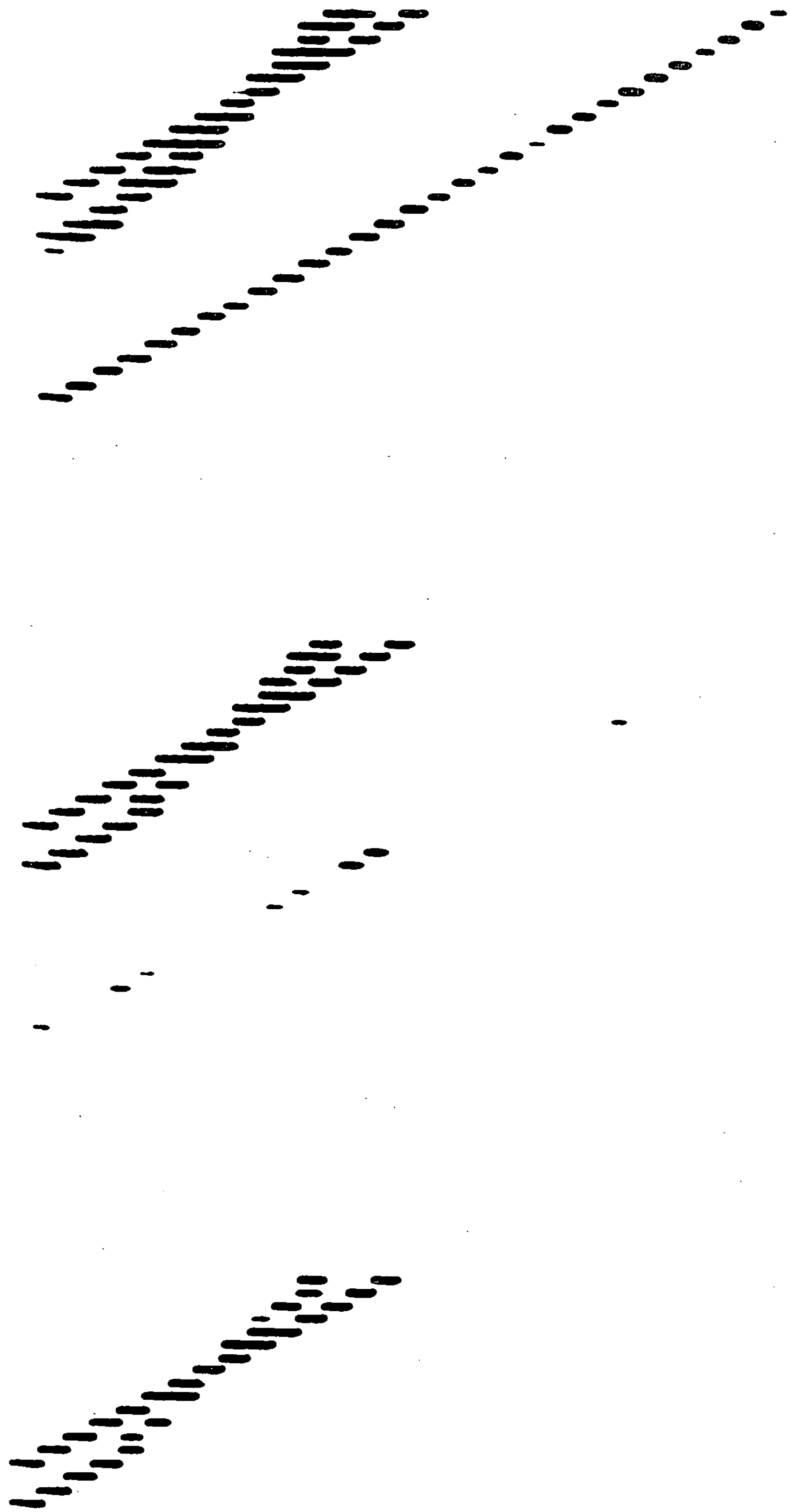

Fig 8b

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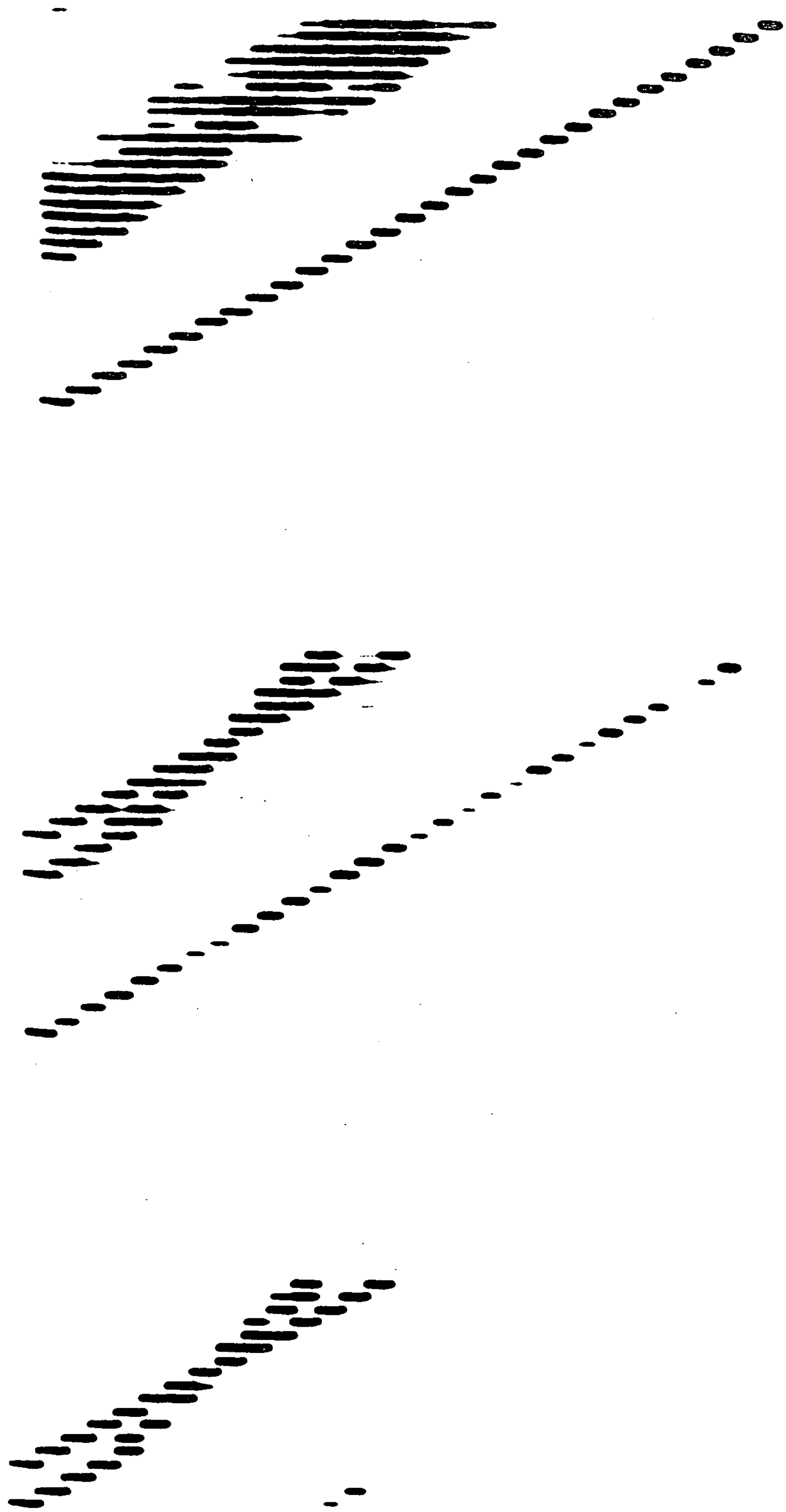

Fig 8c

Fig 8 d

Ball Reg. No. 3-650-62.

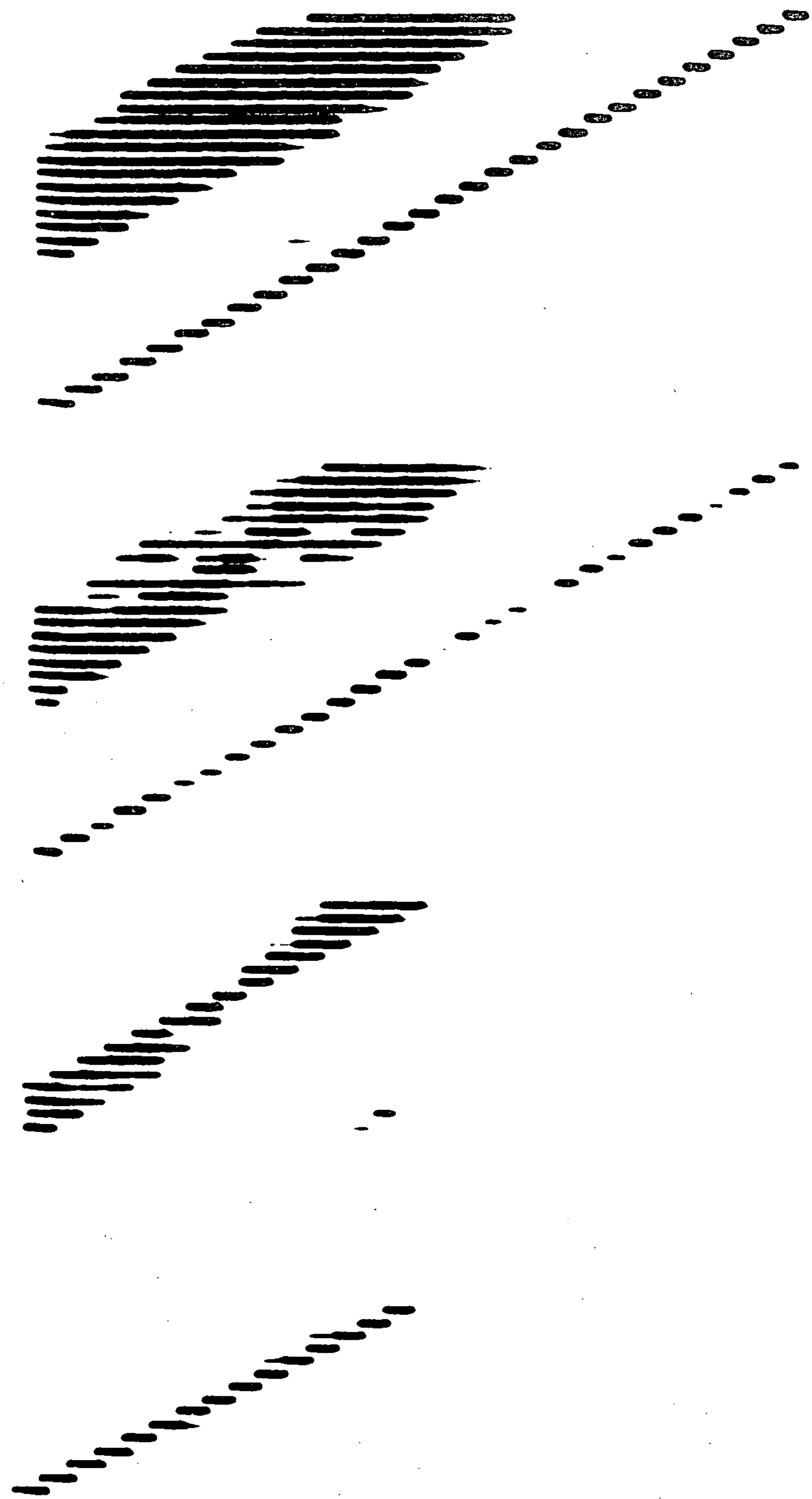

Fig 8e

BNL Neg. No. 3-656-62.

SPECIAL CONTRIBUTION

A Brief History of Positron Emission Tomography

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"The true delight is in the finding out, rather than in the knowing." —Issac Asimov

Shortly before the time of this writing, Michael Ter-Pogossian, PhD, passed away at the age of 71. He was considered by many to be the father of PET and is best known for experiments beginning in the 1950s, which led to the development of PET as a practical diagnostic tool (Fig. 1). In my research of the literature for this article, Dr. Ter-Pogossian's name appeared frequently on many of the landmark publications and I have drawn heavily from his work as a historian and scientist. His death is a great loss to the nuclear medicine community. It is with his achievements in mind, as well as the achievements of many other outstanding scientists, that I have written this article. I have tried to be as accurate as possible in my documentation of events as well as in my interpretation of their significance. I trust that the reader will gain as much as I have from this endeavor.

Key Words: PET; history; instrumentation

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PET is a nuclear medicine procedure which takes advantage of the unique signal produced by the annihilation of a positron and an electron yielding two photons of 511 keV traveling in nearly opposite directions. If the two photons are detected in coincidence, the origin of the event is known to lie within a well define cylinder between the detectors. This electronic collimation eliminates the necessity for absorbing type collimators present on single-photon imaging devices, resulting in some distinct advantages: (a) higher contrast and resolution, (b) detection sensitivity independent of the depth of the activity in tissue, and (c) the ability to correct for the attenuation of the radiation signal. Contemporary PET cameras consist of a series of detector rings which produce tomographic images by reconstructing the distribution of radioactivity from measurements taken at different angles, similar to that used in computerized axial tomographic (CT) imaging.

In addition to the physical characteristic mentioned above, many positron emitting radionuclides exhibit chemical properties that are useful for the study of physiologic processes. The most widely used radionuclides in PET are cyclotron produced such as ^{18}F, ^{11}C, ^{15}O and ^{13}N with half-lives of 109.8, 20.0, 2.0. and 10.0 min, respectively. These are isotopes of elements that are abundantly present in nature and can be incorporated into the organic compounds without significantly altering their structural or biological properties. For example, ^{11}C can be incorporated into acetate or palmitate and will be metabolized by the myocardium in the same manner as the unlabeled natural substrate (*1*). Also, ^{82}Rb is widely used as a myocardial flow agent and is available through a generator infusion system.

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HISTORY

The history of PET started shortly after the moment of creation, the Big Bang. Cosmologists hypothesize that all matter in the universe was contracted into an infinitely small space called a singularity and then exploded producing an enormous fireball at a temperature of 100 billion K. During the very early stages ($t = 10^{-2}$ sec) of this cosmic fireball, the universe was dominated by a great density of energy in the form of radiation. The density was so great that there was an energy equivalent of an electron-positron pair in a volume of space corresponding to the size of electron-positron pair. Newly created beta particles would immediately annihilate creating gamma radiation after the equivalence of energy and matter formula, $E = mc^2$. The energy state was continually alternating from electromagnetic radiation to electrons, positrons and back again to radiation. Not until the universe had expanded, ($t = 4$ min) and hence cooled was it possible for the heavier particles, protons and neutron to exist (*2*). From this boiling sea of nuclear reactions emerged positrons, electrons and the annihilation radiation signal used by today's PET systems.

The development of PET in more modern times took place in phases as a result of advances in physics, mathematics, chemistry, computer science and fundamental biology. Most of these advances were accomplished independently but drove the progress of the other. There were three significant phases in which important advances were made (*3*).

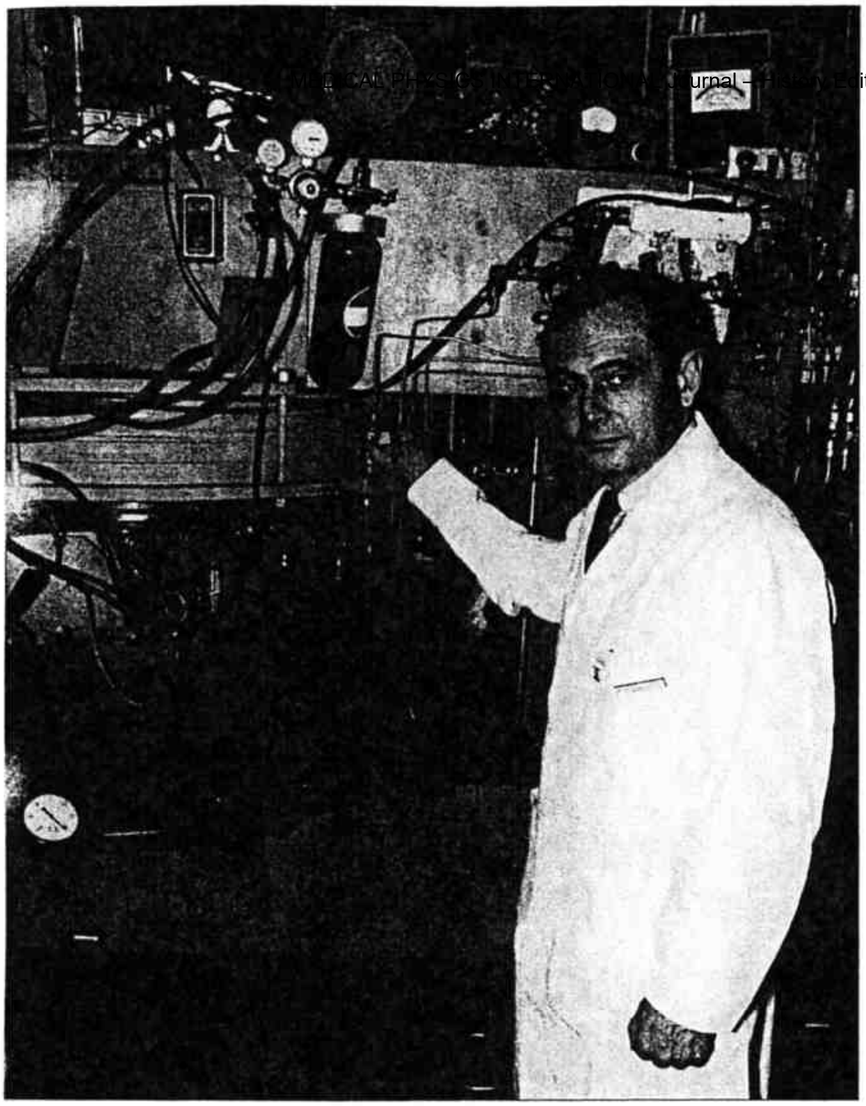

FIGURE 1. Michel M. Ter-Pogossian in the late 1960s. Dr. Ter-Pogossian was a member of the Institute of Medicine of the National Academy of Sciences. During his career he was a recipient of both the SNM Paul C. Aebersold Award for outstanding achievement in basic science in nuclear medicine and the Hevesy Nuclear Medicine Pioneer Award. (Photograph courtesy of the Mallinckrodt Institute of Radiology, Washington University Medical School, St. Louis, MO).

Phase one, late 1920s to the late 1940s: The discovery of the positron and artificial radiation, invention of the cyclotron, recognition that the radionuclides ^{11}C, ^{13}N, ^{15}O as well as ^{18}F were important for the tracing of important biochemical pathways and lastly, invention of the scintillation detector.

Phase two, mid-1950s to the early 1970s: The first installation of a cyclotron in a medical center, use of ^{15}O in biomedical studies, development of single-photon tomography, development of different types of positron scanning devices and development of CT using x-rays.

Phase three, mid 1970s to the present: The development of a positron detection tomograph that incorporated the fundamental features of modern day PET systems, the synthesis of the numerous PET compounds including, 2-[^{18}F]fluoro-2-deoxy-D-glucose and the evolution of the self shielded negative-ion cyclotron for medical uses.

PHASE ONE

In 1929, the physicist Paul Dirac published a paper titled, "A Theory of Electrons and Protons," in which he found two solutions to the equation he was working with that described the behavior of the electron (*4*). One solution corresponded to the electron, which carried a negative charge and one to a then unknown particle carrying a positive charge. Dirac thought that this positive charge might represent the proton. However, he argued against ignoring the unwanted solution to the equation and stated, " Further, in the accurate quantum theory in which the electromagnetic field also is subjected to quantum laws, transitions can take place in which the energy of the electron changes from a positive to a negative value even in the absence of any external field, the surplus energy, at least 2 mc^2 .... " He also noted that the laws of conservation of energy and momentum would require at least two light-quanta to be simultaneously formed (*4*).

Other physicists doubted Dirac's calculations were telling them anything significant about nature and thus ignored the unwanted solution (*2*). This may be explained, in simplicity, by the example of a quadratic equation which ends up with the square root of a number, one being positive and one negative. For example the square root of 9 is both +3 and −3 as each multiplied times itself equals 9. It was not until 1932 that the concept of the positron was postulated by Carl Anderson while studying cosmic ray interactions with a cloud chamber (*5*). While investigating the influence of a magnetic field on the trails left by cosmic rays, Anderson found some trails were bent by exactly the same amount but in the opposite path of the electron. This was of great significance to him, as only a particle with the identical mass but opposite charge of an electron could act in such a way. Anderson called these particles antielectrons or positrons which was then confirmed to be the same particles predicted by Dirac's equation. This novel piece of work earned Anderson his Nobel Prize and in 1933 Dirac and Erwin Schrödinger received the prize for the prediction of this new particle.

In 1934, Irene Curie and Frederick Joliot were credited with the discovery that three elements, aluminum, boron and magnesium, when bombarded by alpha particles emitted by polonium, continued to be sources of penetrating radiation even after the alpha particle sources had been removed (*3,5*). Significantly, the intensity of this radiation decreased as a function of time.

Marie Curie made the following statement regarding these newly discovered radio-elements: "One could only hope that in the future one could obtain by means of tubes generating accelerated particles radio-elements of which the intensity of the radiation would be comparable to that of natural radio-elements. These new substances could then have medical applications and also probably other practical applications." This statement was prophetic as the use of artificially produced radio-elements has formed the foundation of nuclear medicine and proved to be an important tool in biomedical research (*3,5*). It is interesting to note that one of the first artificially produced radionuclides was ^{13}N which was generated by the nuclear reaction $^{10}B + ^{4}He = ^{13}N + ^{1}n^{1}$. This radionuclide which decays with the emission of positrons, is commonly used today in the form, $[^{13}N]NH_3$ as a myocardial perfusion agent.

Motivated by the discovery of this new phenomena, investigators at the University of California in Berkeley used their recently developed cyclotron to produce artificial radionuclides in quantities meaningful to the performance of biological experiments. The cyclotron was developed by Ernest O. Lawrence while at Berkeley between 1930 and 1936 with the intent of transmuting elements. At the time there wasn't any thought given to the production of radionuclides. Ironically, it was only after the news of Irene Curie's and Frederic Joliot's findings that the Berkeley group realized that the transmutations produced by the accelerations of ions in their cyclotron often produced radioactive substances (*3*).

While numerous radionuclides were produced by the Berkeley positive-ion cyclotron, it was ^{11}C, ^{13}N and ^{18}F that received most of the recognition as useful radio-markers for biological studies. In 1939, researchers at the University of California published a preliminary report on the reduction of carbon dioxide by green plants, particularly sunflower, barley and wheat using the radionuclide ^{11}C (*6*). This work was extended in 1940 to green alga, *Chlorella pyrenoidosa*, which was more suited to the quantitative experimentation of photosynthesis. The group allowed the plants to grow in an atmosphere of $[^{11}C]\ CO_2$ in the presence and absence of light. They were able to demonstrate that a reversible carboxylation reaction was the initial step of photosynthesis. Ruben's group also used ^{13}N to study nitrogen fixation by nonlegumenous plants. Cramer and Kristiakowsky labeled ^{11}C to lactic acid to study the synthesis of liver glycogen (*7*). Fluorine-18 was used to study the absorption of fluorides in dentine enamel and bone by Volker et al. (*8*) and the secretion of intravenously injected fluorine in the saliva of cats by Willis (*9*).

Possibly the first use of positron-emitting radionuclides in humans was by Tobias, Lawrence, Roughton, Root and Gregersen in 1945 (*10*). This group used ^{11}C labeled to carbon monoxide to study its fate in man. Several subjects inhaled $[^{11}C]$ CO followed by the inhalation of 100% oxygen. The exhaled $[^{11}C]\ CO_2$ was collected in soda lime while at the same time measurements over the thigh, chest, spleen and liver were performed using a Geiger-Muller counter. The results showed that most of the radioactivity was recovered in the subjects exhaled breath indicating that carbon monoxide uptake in the body is reversible. It is interesting to note that these experiments not only had a theoretical significance but a practical application as World War II was being waged and there was concern about the possible deleterious effects of prolonged exposure to carbon monoxide by soldiers working in tanks, planes, cargo ships, submarines etc.

In spite of the intense activity to produce radionuclides in cyclotrons, there was skepticism regarding the usefulness of the shorter half-lived ^{13}N and ^{15}O as tracers. In "Isotope Tracers in Biology", Kamen states, "Because of its short half-life and because it must be produced by a (d,n) reaction involving the installation like a cyclotron, ^{13}N is too restricted in application to be considered of importance as a tracer for nitrogen." (*11*). Kamen went on to say, "No radioactive isotope of oxygen is sufficient long lived to be useful in tracer work." E.L. Dougherty confirmed this feeling and wrote in "Isotopic Tracers in Nuclear Radiation" that ^{13}N was not a promising agent despite excellent cyclotron yields as it had very limited biological applications and he thought even less of the usefulness of ^{15}O because of its 2-min half-life (*12*).

There was only a limited use of ^{11}C, ^{13}N, ^{15}O and ^{18}F during the mid 1940s to the early 1950s, perhaps because the discovery of ^{14}C offered a more flexible label than ^{11}C for biological experiments (*3*). Other radionuclides such as ^{131}I became available with the development of the nuclear reactor during the Manhattan project, and interest shifted in that direction. This marked the end of the first phase in PET's history as the use of short lived cyclotron-produced radionuclides was considered impractical for biomedical research (*3*).

It is of historical significance to note the G-M counter was the predominant instrument used for the external detection of gamma rays. This device was relatively insensitive to the detection of higher energy gamma photons and would have been unsuitable for the detection of 511 keV photons. Fortunately, the groundwork for a better detector was accomplished at the turn of the century by Ernest Rutherford who visually counted the scintillations produced by interactions of alpha particles with zinc sulfite crystals. Heinz Kallman reported in 1948 that photomultiplier tubes could detect these scintillations individually and amplify them for electronic counting. By 1949 Cassen, Curtis and Reed reported the use of calcium tungstate as a detector for higher energy gamma photons (*13*). The resulting development of the scintillation detector during this period was crucial for the later advancement of dual- and single-photon cameras.

PHASE TWO

By 1950 there was renewed interest in the use of short-lived cyclotron produced radionuclides mainly because of the work started by Ter-Pogossian and co-workers at Washington University in St. Louis. Initially, the group used ^{15}O for the study of oxygen tension in malignant neoplasms in mice using autoradiographic techniques (*3,14*). This effort led to the utilization of ^{15}O-labeled oxygen and other radioactive gases for respiratory and cerebral metabolic studies. Their results were promising enough to lead to the installation of a cyclotron at the Washington University Medical Center during the early 1960s. The cyclotron was installed specifically for the production of short-lived radionuclides for in vivo metabolic studies. The early experiments performed by Ter-Pogossian motivated researchers at Hammersmith Hospital in London to also work with short-lived radionuclides produced by their cyclotron, the first to be commissioned, (1955) in a medical center (*3*). Later, other centers such as Massachusetts General Hospital in Boston and the Sloan Kettering Institute in New York installed small cyclotrons dedicated to the production of the short-lived, positron emitting radionuclides. Older existing cyclotrons at the University of California at Berkley and at Ohio State University were also being used for this purpose. This activity was driven by the recognition that the majority of the metabolic processes important to sustaining life, occur within a short enough time interval to be traced by the short-lived radionuclides. Additionally, chemists became interested in labeling important physiologic molecules with these nuclides and developed rapid procedures to synthesize the compounds (*3*).

It is of interest to note that in 1966, Ter-Pogossian and Wagner published an article in *Nucleonics* titled, "A new look at the cyclotron for making short-lived isotopes" (*15*). The authors argued that, short-lived isotopes had the optimum half-life, decay characteristics and chemical properties needed for medical and biochemical research. Additionally, they promoted the cyclotron as being cost effective with the flexibility to produce isotopes in large quantities. The joint effort by these two noted scientists was indicative of the activity and excitement surrounding not only nuclear medicine but the promise of PET during this time period. This early work by Wagner and Ter-Pogossian helped the evolution and proliferation of the more practical negative-ion cyclotron so important to the future of PET.

Several investigators exploited the distinct advantages inherent to the detection of annihilation radiation over single photon imaging. In 1951 Wren, Good and Handler first reported on the possible use of opposing thallium-activated sodium iodide detectors, (NaI(Tl)) for the localization of ^{64}Cu-phthalocyanime in brain tumors (*16*). Wren hypothesized that, because it was known that two quanta emerged simultaneously and in opposite directions, (to within precision of 1/137 radian), if the two quanta could be counted in coincidence, the source of the activity must lie somewhere along a straight line joining the detectors. From experiments comparing single photon to dual-photon detection he concluded: "Thus, it appears possible to more accurately delimit point sources, and hence extended sources with the technique of coincidence counting of annihilation pairs." Brownell and Sweet had been working independently on the same problem. In 1953 they reported on a positron scanner also designed for the localization of brain tumors (*17*). This device consisted of two sodium iodide detectors mounted collinearly on an adjustable platform which moved in a rectilinear fashion. A printing mechanism recorded the coincidence counting rate on carbonized paper. Brownell thought there were few light element, positron emitting isotopes, with appropriate half-lives. He listed as the most suitable: ^{48}Va, ^{52}Mn, ^{64}Cu, ^{74}As and ^{84}Rb. All of these had half-lives on the order of days or weeks with the exception of ^{64}Cu. His thinking was logical as the equipment being developed at the time, although using coincidence detection for collimation, lacked sufficient sensitivity to satisfactorily image the short half-lived, physiologic nuclides.

In an attempt to improve sensitivity and resolution, different designs of positron cameras were developed. In 1962, Rankowitz et al. designed a positron scanner which consisted of a ring of scintillation detectors (*18*). The system imaged transverse tomographic distributions for the localization of brain tumors. Although the system was limited by under-sampling and the lack of attenuation correction, it did demonstrate the advantages of electronic collimation and its application to tomagraphic imaging. Kuhl and Edwards reported in 1963 on the development of a tomographic scanner designed to image single photon gamma ray emitters (*19*). Their early work clearly demonstrated the advantages of tomographic imaging and they concluded, "With section radioisotope scanning, the images of the body structures should be more clearly defined, and more useful information should be obtained from the study of the liver, brain, thyroid gland and other organs." Even though Kuhl and Edwards' work is linked primarily to single photon systems, their efforts also promoted the usefulness of tomography for dual-photon systems.

Anger and Gottschalk also reported in 1963 on the design of a positron camera for brain tumor imaging (*20*). The system used an 11.5 inch diameter sodium iodide crystal with an opposing compound coincidence detector consisting of 19, 1.75 in. crystals. No collimators or mechanical scanning motion was required and the large crystal permitted the entire brain to be encompassed in one image. The authors reported that the system provided high sensitivity (500 dots per min per μCi), and sharp focus within a predetermined plane. Importantly, the sensitivity was approximately 20 times the average rate per μCi than ^{203}Hg, when used with a 19-hole focused collimator under identical conditions. The system was used to image brain tumor concentrations of ^{68}Ga labeled EDT and was the first application of coincidence detection using a gamma camera.

In 1970 Burham, Aronow and Brownell developed a hybrid positron scanner which used an array of nine crystal pair detectors arranged in columns and moved in a rectilinear fashion. Data was stored on magnetic tape and replayed into an oscilloscope for a timed camera exposure to generate the resultant image (*21*). The device was intended primarily for brain imaging but was envisioned as the first in a series of multidetector instruments for positron scintigraphy of various organs. The authors stated, "We hope that these devices will greatly advance the application of the short-lived nuclides (e.g., ^{15}O, ^{13}N, ^{11}C), with half-lives from 2–20 min." This represented a shift away from the their original position that, only the longer-lived radionuclides mentioned earlier were of potential use. Ter-Pogossian's successful work using oxyhemoglobin labeled with ^{15}O may have provided the motivation for their change in attitude (*3,22*). In spite of the short half-life of ^{15}O (120 sec), Ter-Pogossian and his co-workers demonstrated that regional cerebral oxygen utilization could be reliably measured with external counting devices and stated, "In fact, the short half-life of this label is considered desirable because, in many instances it can be administered in large quantities affording good counting statistics with relatively low exposure of the patient to radiation."

During the early 1970s Ambrose and Hounsfield described a technique in which radiograph transmission measurements were acquired through the head at multiple angles (*23*). From these measurements, absorption values of the tissue density within the head were calculated by a computer and displayed as a series of tomographic slices. By obtaining the absolute values of the tissue's absorption coefficients, tissues of similar density could be separated increasing the sensitivity for the detection of soft tissue abnormalities by approximately two orders of magnitude. The first computerized transaxial tomograph was introduced by EMI Company of England and was of great significance to Radiology and helped to propel PET into its third phase.

PHASE THREE

Instrumentation and radiochemistry characterized the two tracts of rapid development during this period. Advancements built on the momentum generated during the late 1960s and early 1970s. Initially, developments in PET instrumentation were of the greatest significance. These developments were motivated by the recognition that, the positron signal proved to have numerous advantages over conventional radiation, especially for tomographic imaging. Furthermore, as mentioned above, the short-lived radionuclides were confirmed to be important tracers for the study of many physiologic processes.

Between 1972 and 1973 the Washington University group of Phelps, Hoffman, Mullani and Ter-Pogossian built a device, (dubbed PETT II), which used annihilation coincidence detection to generate reconstructed transaxial tomographs (*24*). The unit consisted of a hexagonal array of 24 NaI (Tl) detectors mounted on a horizontal support. Examined objects were placed on a computer-controlled turntable at the center of and perpendicular to the plane of the hexangle. Measurements for attenuation correction were made by placing a thin plastic ring filled with ^{64}Cu around the object. Tomographic images were reconstructed using a Fourier-based approach developed at Washington University, rather than the algebraic base method used on the early CT scanners. Phantom and animal studies demonstrated that this device provided: (a) high spatial resolution that was solely a function of the exposed detector diameter; (b) resolution and sensitivity that were essentially depth independent; and (c) attenuation correction in the reconstructed image that was simple and accurate. Even though the PETT II had humble beginnings, initially constructed in Mullani's garage (Mullani N, *personal communication*, 1996) it proved to be the foundation for the evolution of PET tomographs.

By 1975 the prototypical PET (II) was expanded to the clinically applicable PET (III) whole-body camera reported by Ter-Pogossian et al. (*25*). It consisted of 48 NaI (Tl) detectors placed in a hexagonal array with eight detectors on a side. The detector assembly scanned simultaneously in linear and rotational directions for the necessary linear and angular sampling of data. Data were reconstructed by a convolution based algorithm to generate cross-sectional images of the radionuclide distribution. As its name implies, the detection field of view was large enough to accommodate any position of the human body. The unit exhibited sufficient detection efficiencies to complete scans in 2–4 min with 500,000–2,000,000 counts collected from 10–15 mCi of injected material. This capability was important for the imaging of ^{11}C, ^{13}N, ^{15}O labeled compounds. PET (III) was used extensively for both patient and animal studies at Washington University and later at Brookhaven National Laboratory.

The PET II and III instruments incorporated the fundamental features of modern PET imaging devices. Success was based in part on the contributions of noted scientists working in the field of both single- (Budinger and Gullberg, Keys and Simon, Oppenheim and Harper, Todd-Pokropek, Kuhl and Edwards) and dual-photon instrumentation [Phelps, Mullani, Ter-Pogossian, Hoffman, Brownell, Chesler and Cho (*26*)]. The coincidental development of mini-computers contributed substantially to the success of the PET (III) as well as future PET and single photon imagers. These computers were cost effective, capable of solving the large computational problems associated with reconstruction tomography and essential to the advancement of PET instrumentation.

During the late 1970s and 1980s, advancements of PET cameras resulted in the following designs:

1. A system with a single ring of NaI(Tl) detectors was developed by Cho, Chan and Eriksson (*27*). This design was eventually expanded to multiple rings using the more efficient crystal, bismuth germanate oxide (BGO) reported on by Cho and Farukhi (*28*). BGO represented a significant improvement over NaI(Tl) because (a) it had twice the density allowing smaller crystal size, (b) it had a

comparable scintillation decay constant, (c) it was relatively inert and hydroscopic and (d) it had three times the detection efficiency.

2. Mullani, Ter-Pogossian and co-workers investigated and constructed ring detectors using the faster scintillating crystal, cesium fluoride and a time-of-flight detection scheme (*29,30*). These systems were designed specifically for fast dynamic studies of the brain and heart using the short half-lived ^{15}O and ^{82}Rb, respectively. Please see Appendix A for a further explanation of this technique.
3. In 1976, Muehllehner, Buchin and Dudek introduced a system which used two opposing Anger gamma cameras for the coincidence detection of positron emitters (*31*). Their design consisted of one inch thick NaI(Tl) crystals shielded by a set of thin absorbers (1.27 mm lead and 0.76 mm tin) intended to transmit most of the 511 keV signal while filtering out the scatter radiation from the patient. Projection data was obtained by rotating the detectors around the object. Their system had the advantage of a large axial field of view and a lower cost as compared to the ring design which used multiple small detectors. However, the sensitivity of this design was limited by the necessity for angular rotation.

The evolution of PET system geometry can be characterized by three basic designs: (a) planar, (b) polygonal and (c) stacked circular rings. Typical of PET's history, there were many other contributors who share credit for the success of these designs, including Derenzo (*32*), Lecomte (*33*) and Burnham (*34*). Today the most commonly found systems use either hexagonal or circular geometry with small BGO detectors and emphasize high resolution.

Contemporary systems have evolved to provide (a) spatial resolutions of 4–5 mm, (b) large axial fields of view (greater than 15 cm) and (c) three-dimensional imaging capabilities. Three-dimensional imaging refers to the ability to retract the lead septa housed between detector banks so that all detectors are in coincidence with every detector in all planes of the imaging system. Although dramatically improving sensitivity, this "wide open" imaging strategy also increases the acceptance of scatter and random events adding to the image noise. In spite of this, three-dimensional imaging has demonstrated usefulness in low count studies. These elegant instruments are the end result of many other unmentioned contributors from the related fields of mathematics, computer science, engineering and physics. The future may see PET tomographs that reach the theoretical limit of resolution (approximately 2 mm), provide even better sensitivity and, as temporal resolution improves, incorporate time-of-flight information.

As the progress of PET cameras accelerated so did the complimentary applications of PET radiochemistry and biology. During this period, chemists had become motivated to rapidly label increasingly complex molecules. In 1980, Ter-Pogossian, Raichle and Sobel published an article in Scientific American (*35*) in which they listed 30 compounds labeled with either ^{15}O, ^{11}C, ^{13}N or ^{18}F. Today that list has expanded to several hundred. Probably the most widely used compound to be synthesized was [^{18}F]FDG, an analog of glucose. Fluorine-18-FDG is transported to tissue and phosphorylated to FDG-6-phosphate in a similar fashion as deoxyglucose or glucose. However, unlike glucose it is trapped as FDG-6-phosphate. This compound resulted from the development of [^{14}C]deoxyglucose (DG) and was extensively used by Louis Sokoloff and others to study the energy metabolism of the brain. In 1978, Ido et al. (*36*) first successfully synthesized [^{18}F]FDG and since that time much refinement of the process has been accomplished. Fluorine-18-FDG is now routinely synthesized using the "black-box" technology developed by Padgett (*37*). There has been much interest in using ^{18}F as a label for it is readily produced in cyclotrons, has a reasonably long half-life and possesses properties that are compatible for monitoring many biological processes. Today, over 100 radiopharmaceuticals have been synthesized using ^{18}F.

Sokoloff and his co-workers not only validated [^{14}C]DG as a marker for cerebral glucose metabolism, but in 1977 also developed a comprehensive mathematical model for the measurement of cerebral glucose metabolic rate using [^{14}C]DG (*38*). Since PET provides unique capabilities for the noninvasive quantification of biological processes, it was natural for Phelps and his colleagues in 1979 to extend the principles established by Sokoloff to the measurement of cerebral glucose metabolic rate in humans using PET and [^{18}F]FDG (*39*). The subsequent validation of this model by Phelps allowed for the accurate, in vivo quantification of glucose metabolism using PET technology. At the present time, additional mathematical models have been developed for use with other compounds for applications such as receptor imaging.

An important catalyst to the progress of PET radiochemistry and instrumentation was the coincidental evolution of the cyclotron from the large, high energy, multiparticle, positive-ion to the smaller, more practical, lower energy, single particle, negative-ion type. See Appendix B for an explanation on how the cyclotron works. Early cyclotrons were able to accelerate multiple particles such as, protons (^{1}H), deuterons (^{2}H), tritron (^{3}H) and alpha particles (^{4}H) up to energies ranging from 15 to 40 MeV. This capability allowed for the production of both the short- and longer-lived radionuclides and, as mentioned earlier, these early cyclotrons were the first to be installed in a medical center. As interest in using the physiologic radionuclides, ^{15}O, ^{13}N, ^{11}C and ^{18}F grew it was recognized that accelerators designed to produce these positron rich isotopes could be constructed, installed and operated at a lower cost. Between 1986 and 1987 CTI Corporation of Knoxville, TN introduced the first cyclotron designed specifically for the production of PET isotopes. These 11-MeV, negative-ion, proton-only units had the following advantages over positive-ion systems:

1. They could be self-shielded and conveniently placed whereas the older units, because of high-radiation levels, needed to be in a room (usually below ground level), with up to 2-meter thick concrete walls.
2. The installation and operating costs were greatly reduced.

3. Serviceability was increased due to the substantially lower radioactivation of their internal parts.
4. They were controlled by PC technology and could be operated by a qualified technologist.

Currently the trend is for even smaller and less expensive cyclotrons. For instance, in 1995, CTI introduced their new "deep valley" design which requires only a single unshielded room, reduced power consumption (67% of their older unit), boasts of a graphic interface providing even more convenient operator control and cost about 40% less to purchase (Odeh N, *personal communication*, 1996). The success of these negative-ion cyclotrons has provided more affordable access to the physiologic radionuclides and will most likely continue to be instrumental to the proliferation of PET centers.

CONCLUSION

PET's inherent strengths, which have been enjoyed by the scientific community, have not been fully recognized by the general medical community as being essential to the health care system. An uncertain future for PET has resulted. This uncertainty can be linked to the following:

1. In most cases, PET requires the presence of an onsite cyclotron.
2. The modern PET tomograph although elegant, is expensive.
3. Third-party reimbursement for clinical studies is not fully actualized
4. There are other competitive nuclear medicine procedures that provide similar information.

These points have not diminished the importance of PET but have merely served to slow its growth. Despite these obstacles, there continues to be strong scientific and clinical interest in PET. At the 1996 SNM Annual Meeting, for example, there were 150 presentations involving [^{18}F]FDG, with 88 presentations in oncology, 49 in neuroscience and 23 in cardiology (*40*). Other radiopharmaceuticals have shown promise for oncological uses including, [^{11}C]methionine, [^{18}F]fluoroestrodiol and [^{18}F]fluoromisonidazole (*41*). Work by Gambhir and his colleagues (*42*) has demonstrated the potential cost-effectiveness of PET. They found that when both [^{18}F]FDG and CT studies were performed for the staging and management of non-small-cell lung carcinoma, there was a saving of $1154 without loss of life expectancy.

The vibrant interest in [^{18}F]FDG has helped to motivate industry to produce Anger-type gamma cameras with coincidence detection capabilities. Two systems are currently on the market and will potentially provide greater access to PET technology by the general nuclear medicine community. This fact coupled with a *regional* cyclotron approach to the distribution of [^{18}F]FDG and other ^{18}F-labeled radiopharmaceuticals, may well serve as the engine which helps drive PET into its fourth phase, a clinically accepted imaging modality.

APPENDIX A

Time-of-flight (TOF) systems take advantage of the fact that if the difference between the arrival times of the two annihilation photons can be measured, then the spatial localization of the event can be estimated. This constrained estimation negates the necessity to spread the localization of the positron source over the entire coincidence line between the detectors improving the signal to noise ratio (*43*). Since TOF requires very fast temporal resolution, 600–800 psec compared to 5–20 nsec for conventional systems they have the additional advantage of reducing contributions due to random events. This capability is valuable for studies involving very high counting rates.

APPENDIX B

Cyclotrons take advantage of the fact that a charged particle moving at a constant velocity in a plane perpendicular to a homogeneous magnetic field will describe a circle. The radius of the circle is given by:

$$R = mcv/qB.$$

Where m = particle's mass, c = speed of light, v = particle's velocity, q = particle's charge and B = the strength of the magnetic field. In the cyclotron there is a continuous production of ions (charged particles) at a central point located between the two poles of a strong magnet. Between the poles and in a plane perpendicular to the magnet are two hollow box-shaped metal electrodes called dees, which have a high oscillating potential and reside in an evacuated chamber. The ions are attracted or repelled by the dees based on their overall charge. For each transit through the dees, the ions are accelerated, gain velocity and consequently the curved path they follow increases in radius. When the ions reach their maximum energy, just inside the circumference of the dees, they are deflected from their orbits by various means on a path through the beam line and towards the target (*43*). In the case of a negative ion (a proton with two electrons) cyclotron, the electrons are stripped off by passing them through an electrically charged carbon foil. The result is a proton beam which is then directed toward target material, normally a liquid or gas which undergoes nuclear transformation to create the positron emitting radionuclide.

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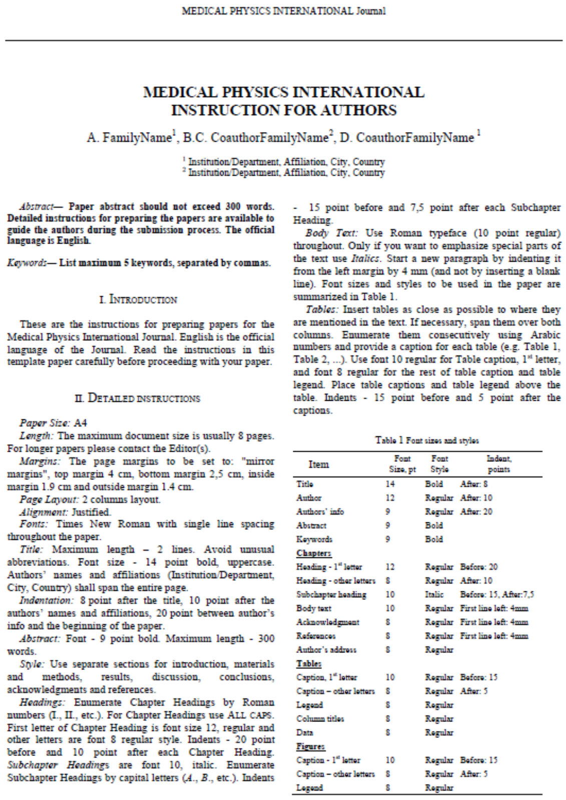

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Author	12	Regular	After: 10
Authors' info	9	Regular	After: 20
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Keywords	9	Bold	
Chapters			
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Heading - other letters	8	Regular	After: 10
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Legend	8	Regular	
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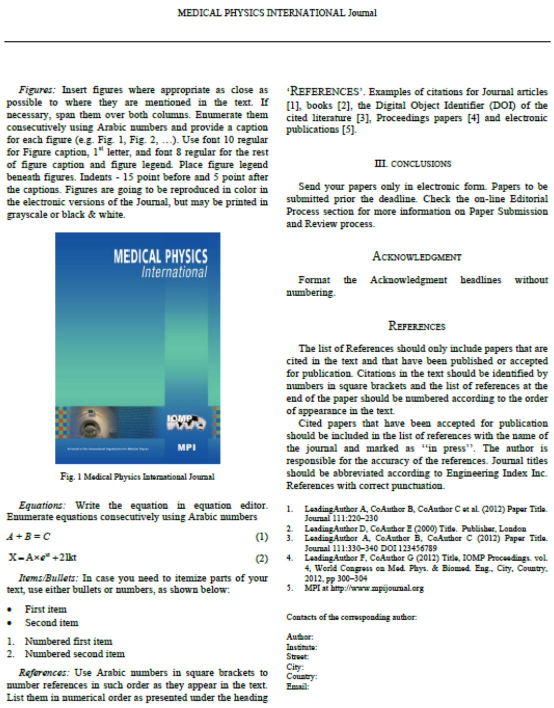

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