

HISTORY OF DENTAL RADIOGRAPHY: EVOLUTION OF 2D AND 3D IMAGING MODALITIES

R. Pauwels¹

¹ Aarhus Institute of Advanced Studies, Aarhus University, Aarhus, Denmark

Abstract— Dental radiography is one of the most frequently performed type of medical imaging. The teeth and associated structures form a unique anatomical complex, being in direct contact with an extensive intra-oral microbiome as well as outside agents. Oral pathology covers a wide array of diseases and trauma to the teeth, gums, jaw bones, and associated structures such as salivary glands and temporomandibular joint. Dentistry has evolved into a highly specialized profession, comprising general practitioners, orthodontists, periodontists, prosthodontists, endodontists, oral & maxillofacial surgeons, pediatric dentists, and others. Furthermore, in many countries, oral radiology is recognized as a specialty, acknowledging the need for adequate training and experience in the diagnosis and treatment planning of the wide array of oral diseases. Nowadays, several dental radiographic techniques are used in practice to complement the clinical examination, with the most frequent modalities being unique to this profession (*i.e.* intra-oral and panoramic radiography).

Considering the high diagnostic efficacy of dental radiographs, it is to no surprise that they were among the first X-ray images obtained of humans, and that this occurred mere days after Röntgen's report regarding his discovery. Whereas the first recorded dental radiograph was not considered to be of diagnostic image quality, and required an exposure time of 25 min, it took only a few weeks until images with demonstrable diagnostic benefit were produced. After the initial hype of medical X-ray application had passed, it took several years before radiography became an integral part of dental practice. When it did, however, rapid improvements were made to each aspect of the radiographic imaging chain, and new techniques were developed to address specific practical or diagnostic challenges in dentistry. This review covers the history of dental radiography, and the evolution of 2D and 3D imaging modalities used in dentistry throughout the past 125 years.

Keywords— Dental imaging, intra-oral radiography, panoramic radiography, cone-beam computed tomography, imaging technology

CONTENT

- I. A NEW KIND OF RAYS (1895)
- II. THE HAND(S) WITH THE RING – THE FIRST HUMAN RADIOGRAPHS
- III. THE FIRST DENTAL RADIOGRAPHS: THE EARLY ADOPTERS
- IV. THE PIONEERING WORK OF DENTISTS IN RADIOPROTECTION
- V. INTRA-ORAL PROJECTION TECHNIQUES
- VI. EVOLUTION OF DENTAL (INTRA-ORAL) X-RAY UNITS
- VII. EVOLUTION OF DENTAL (INTRA-ORAL) X-RAY IMAGE RECEPTORS – FROM PLATE TO PLATE
- VIII. HISTORY OF PANORAMIC RADIOGRAPHY
- IX. OTHER EXTRAORAL RADIOGRAPHIC TECHNIQUES
- X. DENTAL TOMOGRAPHY
- XI. CONE-BEAM COMPUTED TOMOGRAPHY
- XII. RADIOLOGICAL VIEWING/DISPLAY SYSTEMS

I. A NEW KIND OF RAYS (1895)

Wilhelm Röntgen's discoveries, as well as the contributions by other contemporaries, have been extensively covered in literature and will not be reiterated in excessive detail in this paper. Nonetheless, it is pivotal to start our narrative on Friday November 8, 1895; in his laboratory in Würzburg, Germany, Röntgen was investigating fluorescent effects of cathode rays generated by a Crookes-Hittorf tube. Covering the tube with cardboard, he did a quick check to ensure the set-up was light-tight by darkening the room and passing a charge through the tube. While preparing the next step in his experiment, a flicker caught his eye. He noticed that the faint light came from a barium platinocyanide screen that he intended to use in a subsequent phase of his experiment. As this screen was nearly 3 m away from the tube at that time, he correctly deduced that this effect could not have been due to cathode rays, which travel only a few cm in air. A few weeks of further experimentation in total seclusion resulted in the submission of his seminal paper on December 28, 1895, and its publication three days later [1]. The impact of this paper cannot be overstated. The speed at which the news of his discovery spread was astounding, considering that this discovery predates the first e-mail by 75 years and the world wide web by almost 100 years.

Not only did fellow scientists eagerly attempt to reproduce the experiments described by Röntgen mere weeks into 1896, rapid development of tubes allowing for a more consistent and efficient generation of these new rays took place [2].

Whereas Röntgen has received most of the credit for the discovery of X-rays, the role of several predecessors should be recognized (Fig. 1), including but not limited to:

- Sir William Morgan and Michael Faraday: believed to be among the first researchers who generated X-rays (1795 and 1800, respectively).
- Wilhelm Hittorf (1870) and William Crookes (1879): implemented modifications to vacuum tubes and generated X-rays during their experiments. The latter even noticed the fogging of photographic film that was left in the vicinity of his experimental set-up, but did not make the connection that Röntgen did, even complaining to the film manufacturer regarding the poor quality of their product.
- Philip Lenard (1890s) studied cathode rays, and was the primary inspiration to Röntgen's experiment, which was essentially a repetition of Lenard's work with a different type of tube (*i.e.* a Crookes-Hittorf tube with a thicker glass wall). The reason why Lenard did not notice the production of X-rays has been attributed to the use of a material that, unlike barium platinocyanide, shows no fluoresce from X-rays.
- Arthur Goodspeed and William Jennings (1890) accidentally created a radiograph, showing the outline of two coins, by leaving a photographic plate in the vicinity of a Crookes-Hittorf tube [3].

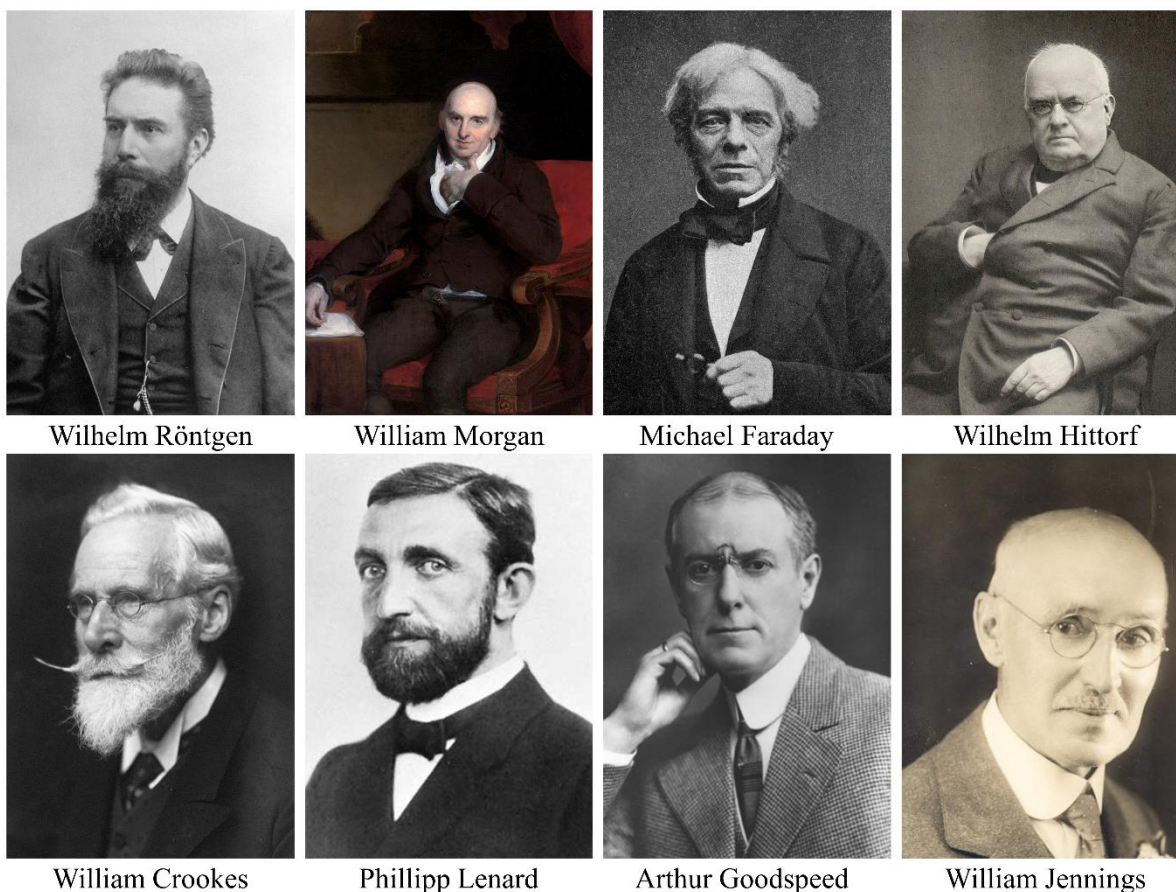


Fig. 1 Non-exhaustive overview of pioneers in the discovery of X-rays. Public domain.

II. THE HAND(S) WITH THE RING – THE FIRST HUMAN RADIOGRAPHS

With the knowledge we have now about the dangers of exposing living tissues to X-rays, it may seem that Röntgen was a bit too eager in finding a test subject to undergo exposure to rays with unknown properties. However, at the time of his discovery, nothing was known regarding the nature and interactions of X-rays, let alone the dangers. In his excitement, Röntgen convinced the person that was literally and figuratively closest to take up the role of test subject. His wife, Anna Bertrand Röntgen, has gone down in history as the first person that underwent X-ray radiography on December 22, 1895, by placing her left hand on a photographic plate for 15 min. However, it is more than likely that Röntgen acquired an image of his own hand first [4]; the post-mortem burning of his records at his own request makes this hard to verify. Nonetheless, it was Mrs. Röntgen's radiograph that was distributed to colleagues, with her wedding ring on prominent display (Fig. 2). For a period of time, these images produced by a type of radiation other than visible light were referred to as 'skiagraphs'.

One can find a second radiograph showing a hand with a ring in literature, which is often incorrectly annotated as being the one Röntgen took of his wife. While it was indeed Röntgen who acquired this image, the hand belonged to Albert von Kölliker, a Swiss anatomist and friend of Röntgen (Fig. 2). This radiograph was made at a public lecture before the Würzburg Physico-Medical Society on 23 January 1896. One can see drastic improvements in image quality between the two hand radiographs, taken only one month apart. The contrast between bone and soft tissues, as well as the clear depiction of the 'foreign body', immediately caught interest of the medical community. Within days, exposures were made of various body parts, including the visualization of fractures, the localization of bullets in injured soldiers, and even early attempts at radiotherapy [5].

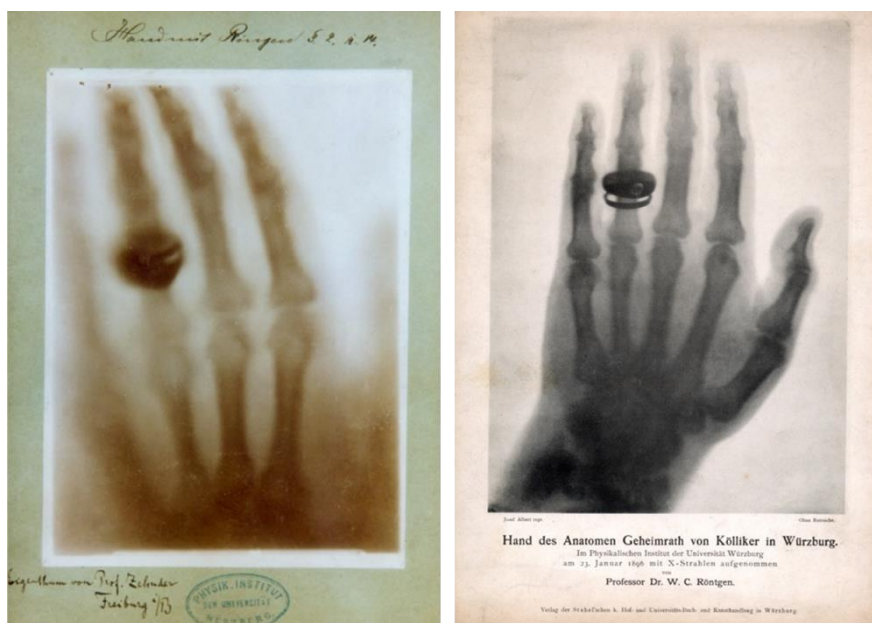


Fig. 2 Left: X-ray of Anna Bertrand Röntgen's hand (1895-12-22). Right: X-ray of Albert von Kölliker's hand (1896-01-23).

III. THE FIRST DENTAL RADIOGRAPHS: THE EARLY ADOPTERS

Two weeks after the publication of Röntgen's discovery, the German dentist *Otto Walkhoff* acquired a radiograph of his own teeth with the help of Fritz Giesel. An exposure time of a whopping 25 min was used (Fig. 3). A lack of diagnostic quality of Walkhoff's blot-like 'bitewing' image can be perceived. Subsequent attempts by fellow pioneers showed rapid improvement of the diagnostic image quality. In 1896, Walkhoff and Giesel established the first dental X-ray laboratory in the world. Later-on, Walkhoff also produced extra-oral radiographs [6].



Fig. 3 Left: Otto Walkhoff. Right: Walkhoff's dental radiographs.

Across the Channel, an English dentist named *Frank Harrison* experimented with dental radiography in early 1896. He presented his findings at the Annual General Meeting of the Midland Branch of the British Dental Association 26 June 26, 1896 [7]. He mentioned in particular the potential applicability of dental radiography for artificial crowns, endodontic treatment, and eruption issues [8]. Furthermore, he provided details regarding the acquisition procedure:

"The film is cut to the required size and enclosed in black paper and then covered with rubber dam; if in the upper jaw a small square simply laid over the film is sufficient to protect it, but if in the lower jaw, it must be completely enclosed in rubber. The whole is then held in position with a frame of stent which has been previously adjusted to the required area and held in place by closing the teeth upon it much after the form of an interdental splint." (F. Harrison, as quoted by Figures & Smith [8])

Around the same time, the physicist *Walter König* performed tests on a wide variety of radiographic applications; among the objects he exposed were different animals, paintings and Egyptian mummies [9]. In March 1896 at the Physical Society of Frankfurt, König published an overview of his work [10], containing radiographs of the anterior teeth of upper and lower jaw (Fig. 4). König's adaptation of the Crookes-Hittorf tube, containing an angled platinum disc, allowed the exposure time to be reduced considerably [11]. The radiographs, in his words:

"are not only able to prove the position and the form of the fillings in the teeth but we are also able to examine parts of the teeth which are sticking into the jaw bones ...". (W. König, as quoted by Forrai [11]).

In the US, several forerunners in dental radiography can be mentioned. *C. Edmund Kells* [12], an American dentist, was informed of Röntgen's discovery on 6 January 1896 by attending a presentation on Röntgen's discovery by Brown Ayres, a physicist at Tulane University. Kells immediately took action in exploring the potential use of X-rays in dentistry, procuring equipment for generating X-rays with the help of Ayres, and acquiring an intraoral radiograph of a living subject (*i.e.* his dental assistant). He later estimated that this occurred in April/May 1896 [13], using a film holder he developed himself that allowed the patient to swallow during the 15 min of exposure. Furthermore, to stabilize the head, a thin board was placed between the tube and the face, which could be considered as one of the first (albeit inadvertent) uses of X-ray filtration. Kells started demonstrating his radiography technique to eager audiences, including the first clinic in which dental radiography

performed on a patient was shown (July 1896; Southern Dental Association annual meeting). By emphasizing the need for parallel film placement as well as minimal object-film distance he can be considered as the first pioneer of the paralleling technique described several years later by Price [14] and McCormick [15]. He also advocated the use of holders for proper film positioning (Fig. 5) and designed an aluminum/rubber-based film holder [16]. Furthermore, he is alleged to be the first to propose the simultaneous use of two films for the purpose of record keeping.

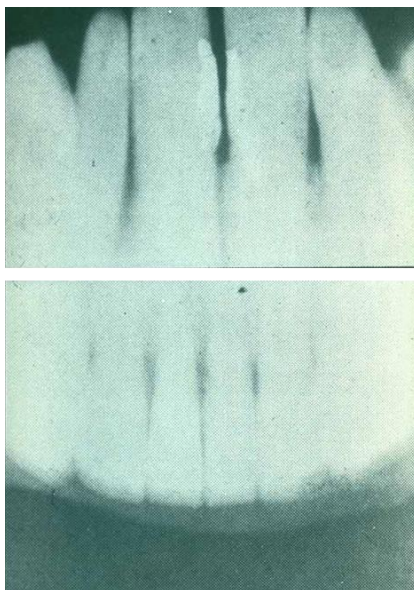


Fig. 4 König's dental radiographs

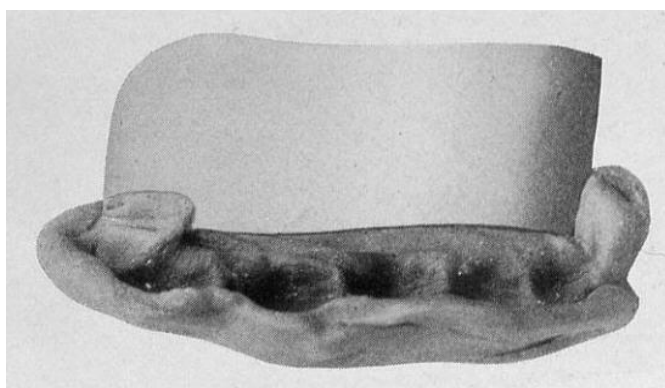


Fig. 5 Kells' film holder

William J. Morton presented intraoral radiographs (Fig. 6, 7) acquired of a dry skull at a lecture for the New York Odontological Society on 24 April 1896. One of his earliest quotes regarding the potential of radiography in dentistry was:

“Already painless dentistry is within your grasp by aid of electricity and simple anesthetics, and now the X ray more than rivals your exploring mirror, your probe, your most delicate sense of touch, and your keenest powers of hypothetical diagnosis.” (W.J. Morton, as quoted by Martinez [17])

His work was published in the journal Dental Cosmos [18], mentioning the applicability of radiography for impacted/unerupted teeth, inflammatory jaw lesions, necrotic bone, and endodontic applications (detecting broken instruments in root canals as well as fillings beyond the apical foramen)[19]. Kells expanded on the endodontic applications by being the first to determine the working length of a root canal using a radiopaque wire. In 1896, Morton published “The X-Ray or Photography of the Invisible and Its Value in Surgery” along with Edwin W. Hammer. This highly informative textbook was seemingly aimed at researchers and medical/dental professionals, containing operational instructions as well as an overview of clinical applications [20].



Fig. 6 Morton's radiograph, showing an artificial crown on a molar [18].

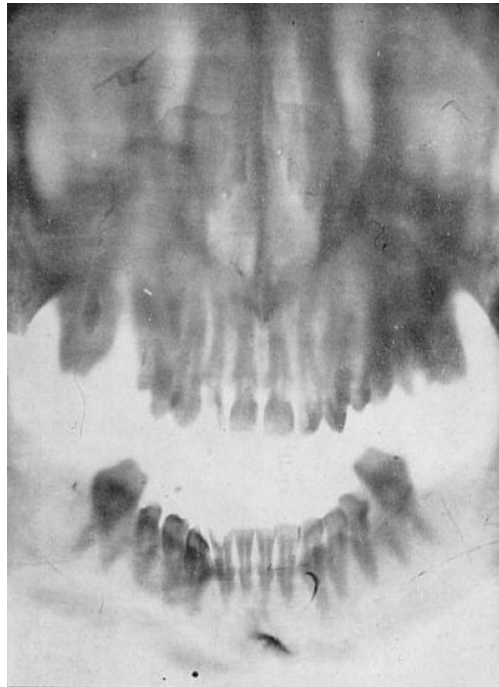


Fig. 7 Skiagraph showing upper and lower jaw teeth.

William H. Rollins, a Boston-based dentist, was another early adopter of dental radiography. In July 1896, he showed the design of an intraoral cassette with accompanying fluoroscope, which could be used to visualize the posterior teeth (Fig. 8); for more on dental fluoroscopy, see section V. Rollins also designed an X-ray tube arm, with a bracket for wall mounting and the use of a (rectangular) collimator, which was never commercially manufactured (Fig. 8). Rollins' legacy is further expanded upon in section IV.

Weston A. Price [21] was at a forefront of radiographic record keeping by meticulously labeling the radiographs he acquired using a thin copper wire, ensuring that the images could not be mixed up. He is also considered as the creator of the bisecting-angle technique described further below. He was among the first to acknowledge the expertise required to interpret dental radiographs.

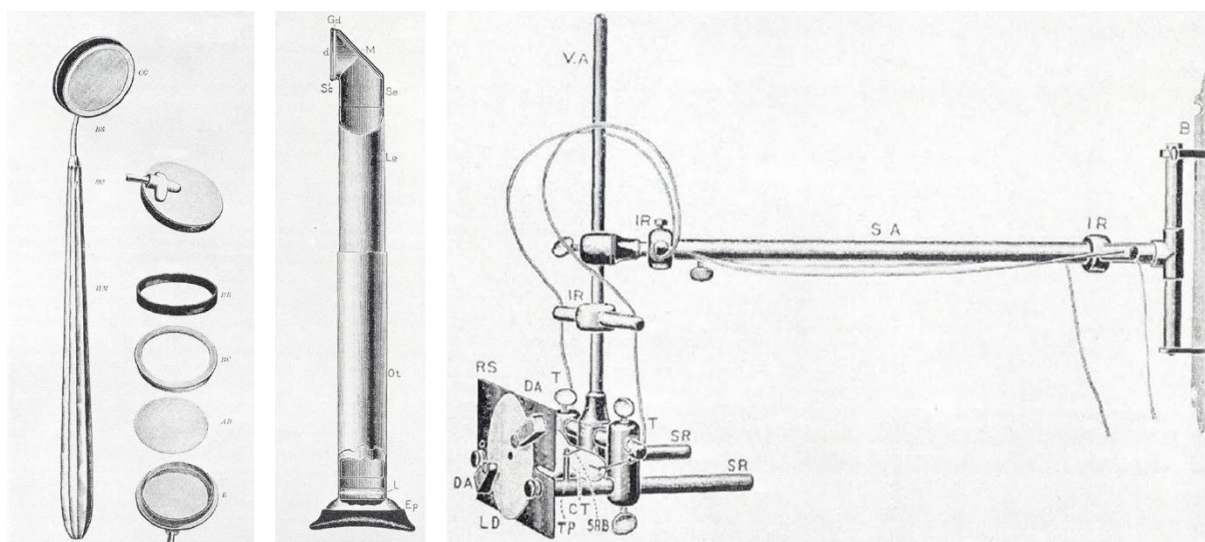


Fig. 8. Left: intra-oral cassette/fluoroscope designed by Rollins. Right: tube arm and bracket proposed by Rollins; notice the use of collimation.

IV. THE PIONEERING WORK OF DENTISTS IN RADIOPROTECTION

Early X-ray tubes had to be recalibrated before each exposure, a practice then referred to as “*setting*”. This was typically done by placing the operator’s hand in front of a fluoroscope and adjusting the tube current until a clear radiograph was shown. Furthermore, it occurred that dentists held the intra-oral plate or film in place using their own fingers during the minutes-long exposure. It is to no surprise that many of the early adopters of X-ray imaging had to pay a heavy toll for their groundbreaking work [11].

One of the most well-documented cases is that of *C.E. Kells* himself (Fig. 9), whose ordeal started with a lesion on his left thumb found in 1908. Soon thereafter, other lesions that were not responsive to treatment appeared on the same hand, eventually leading to a series of amputations. Kells practiced dentistry for several more years, using custom instruments that could be attached to his deteriorating left hand. Eventually, the hand was amputated, followed by his entire left arm being removed in 1926. Later in his life, his right hand started showing similar effects. Throughout the remainder of his life, despite constant pain, Kells kept up his exemplary work ethic, resulting in a bevy of inventions (*e.g.* the suction apparatus) and pivotal contributions to dental literature. In an era of excessive tooth extraction due to the popularity of the focal infection theory, he advocated the use of (conservative) root canal therapy aided by radiography. Near the end of his life, Kells himself published reported on the effects of radiation, distinguishing between early and late effects [22,23].

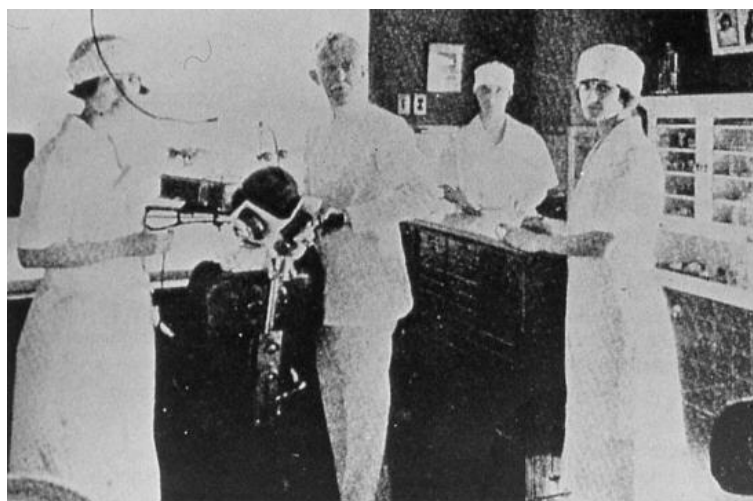


Fig. 9 C.E. Kells at work; one can notice the damage to his left hand caused by repeated X-ray exposure.

W.H. Rollins was a true forerunner in radiation protection, having introduced several principles that are still applied. Between 1896 and 1904, he was highly active in the field, publishing ca. 180 articles on ‘X-light [sic]’. After noticing burns

on his body in exposed regions, including his hands, he linked these effects to X-rays in a letter to the editor in the Boston Medical and Surgical Journal [24]. In this paper, with the candid title “X-light kills”, he detailed an experiment involving guinea pigs, concluding that “when electricity is excluded, death can be produced with x-light without burning.” Two years later, he published his findings regarding the effects of X-rays on the eye lens [25]. He proposed the use of shielding of the operator’s eyes (*e.g.* using lead-lined glasses), the tube and the patient, a principle which is still used in current radioprotection. Furthermore, he advocated the use of proper beam collimation to avoid exposure to areas of the body outside the region of diagnostic interest, which is one of the most efficient practical applications of the ‘optimization of exposures’ principle. Unfortunately, Rollins was largely ignored by his colleagues; several decades later, after the atomic bombings of Hiroshima and Nagasaki, the interest in dental radioprotection resurged. Perhaps owing to his caution regarding the harmful effects of X-rays, Rollins did not suffer the same, excruciating fate of Kells and many other contemporaries [26,27].

V. INTRA-ORAL PROJECTION TECHNIQUES

A. Conventional Projections

In 1904, *Weston A. Price* proposed an isometric X-ray projection technique, which later gained popularity under the name ‘bisecting-angle’ (Fig. 10). This technique was introduced due to practical difficulties in having the image receptor placed parallel to the long axis of the teeth, especially in the upper jaw. Whereas this practical issue has recently reemerged with the use of (relatively bulky) solid-state receptors, a ‘rectangular’ technique has been favored over a revisit to the bisecting-angle technique [28]. With the rectangular technique, the focus is on ensuring perpendicularity between X-ray beam and receptor, regardless of tooth orientation.

Franklin W. McCormack, a medical technician, focused on the application of the *paralleling technique* (Fig. 10) in intra-oral dental radiography. This was facilitated through the attachment of the film to a rigid metal plate, with the added benefit of reducing backscatter. He advocated the use of long source-skin distances (36” or ca. 91 cm) in a 1920 paper [15], mentioning several benefits: reduced X-ray burns when making multiple exposures, improved image quality owing to beam hardening, and avoiding overlap of the zygomatic bone with the apices of the maxillary molars [29]. *Gordon M. Fitzgerald* was in close contact with McCormack throughout his career and applied his technique to actual dental practice. He also advocated the use of high kV (80-100 kVp) X-rays. However, for several decades, dental X-ray tubes operated at a much lower voltage; the low tube output coupled with the limited film speed at the time necessitated the use of short source-detector distances (SDD) of 10 cm and below (*i.e.* ‘short cone’ units). At such short distances, the bisecting-angle technique was preferred due to its lower distortion of the root. Subsequent technological improvements made it possible to use an SDD of ca. 20 cm (‘long cone’), which is considered the standard today. Along with this increased SDD, the paralleling technique became the most common projection technique. Whereas SDDs of 30-40 cm were proposed they proved to be impractical in a confined dental environment, even with the focal spot at the back side of the unit as described in an article by *AG Richards* in 1966 [30]. Neither the slight dose reduction achieved with such an ‘extra-long cone’, nor the improved projection geometry was enough to overcome this practical limitation, resulting in little or no commercial success [31].

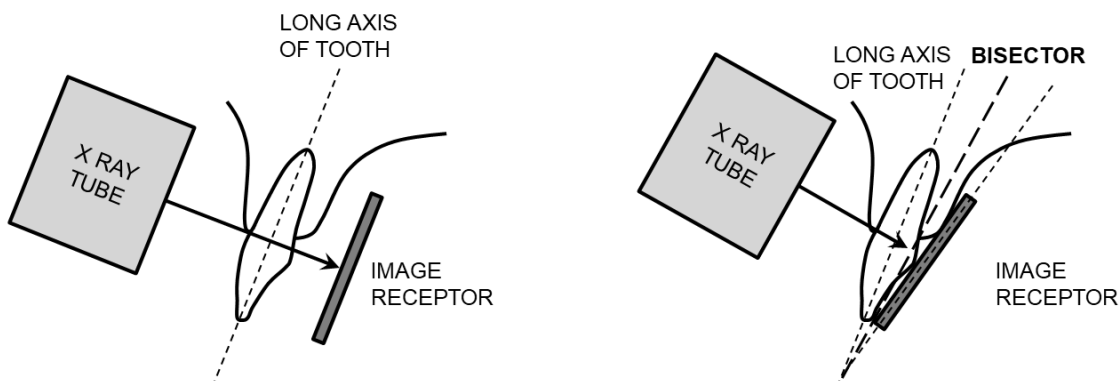


Fig. 10 Left: the paralleling technique, in which the X-ray beam is perpendicular to the long axis of the tooth as well as the image receptor. Right: the bisecting-angle technique, in which the X-ray beam is perpendicular to the bisector of the tooth axis and receptor.

Out of the three types of intra-oral radiographs used today (*periapical / occlusal / bitewing*), the first two were employed from the start, albeit with somewhat inconsistent positioning of the receptor. *Howard R. Raper*, considered among the first dental radiology ‘specialists’, proposed the development of a bitewing film to Eastman Kodak in 1925, with the aim of

visualizing interproximal caries. He also invented an anglemeter that could be used for proper angulation of the X-ray beam when using the bisecting-angle technique [29].

As shown in Fig. 5, *film holders* were used early-on; commercial film holders have been used for decades (Fig. 11 & 12), although several dental offices still do not make use of them (Fig. 12). A UK study in 1994 involving four types of film holders showed differences in practicality and patient comfort, with the ‘Superbite’ holder showing the highest performance [32]. In 2009, a study in Lithuania reported that 32.7% of dental practitioners had the patient hold the receptor with their finger, and 48.0% used film holders and the patient’s finger alternatively [33].

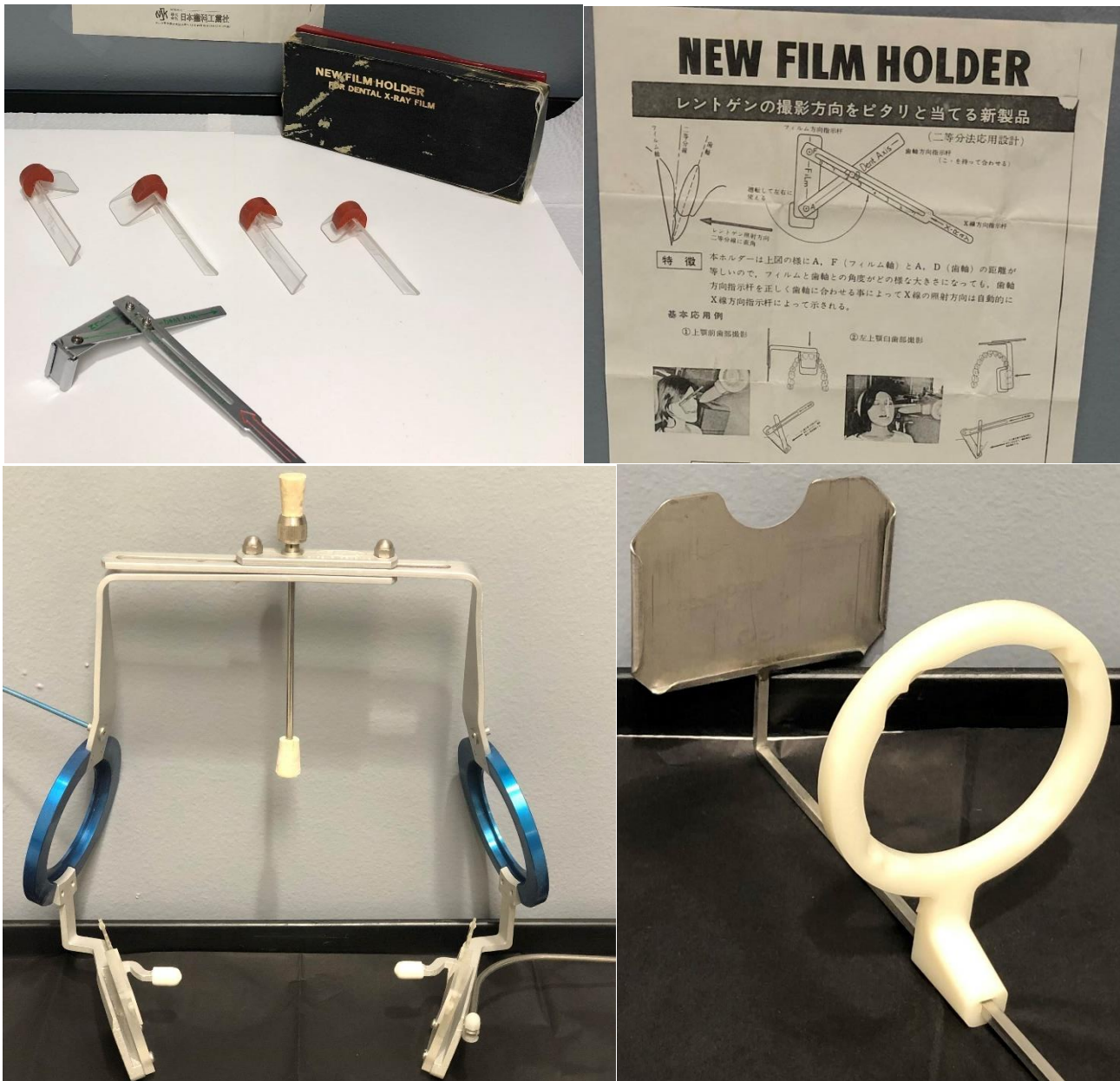


Fig. 11. Top: Vintage film holder. Bottom left: temporomandibular joint film holder and positioning device. Bottom right: occlusal film holder. Courtesy of S. Anamali (University of Iowa).



Fig. 12 Left: receptor holders and positioning devices used in petiapiical (top) and bitewing (bottom) radiography. Courtesy of P. Sinpitaksakul (Chulalongkorn University). Right: Despite the large difference between beam area and receptor area, misalignment of the beam (collimator cut / beam cut) can still occur when positioning devices are not used.

B. Parallax technique

Despite the immeasurable enthusiasm regarding the use of X-rays in medicine, the limitations of projection radiography became apparent quickly. To visualize three-dimensional relationships, the use of complementary angles and stereoscopic viewing (Fig. 13) was proposed by *W.S. Hedley* in 1898 [34]. *C.A. Clark* elaborated on the parallax concept in 1910 [35]. Common application in dentistry include the determination of the relative position of unerupted teeth (*i.e.* buccally / palatally to, or in line with, erupted teeth), and the visualization of multi-rooted teeth. Both horizontal and vertical parallax techniques have been employed [36], and different rules for interpreting the multiple radiographs have been defined, such as:

- *Same Lingual Opposite Buccal (SLOB)* [37] or *Buccal Always Moves Away (BAMA)*: considering radiographs of two objects acquired at different angles, the object furthest from the tube will appear to move along with the tube and vice versa. This concept was introduced by Clark in his 1910 paper through the use of three radiographs [35]. AG Richards revised the rule in 1952, simplifying the technique to only two radiographs [38,39].
- *Mesial-Buccal-Distal (MBD)* [40]: for an exposure obtained at a slight angle to the mesial surface, the buccal root is situated distally.



Fig. 13 Ritter intra-oral 'stereoscope and diagnostic lamp' (ca. 1930, pre-patent [41]), used for pseudo-3D diagnosis based on multiple radiographs until at least the 1950s. Pictures and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [42].

C. Dental fluoroscopy

After its invention by *Thomas Edison*, fluoroscopy was used in medical radiography early-on. A fluoroscope consists of a calcium tungstate screen, allowing for real-time X-ray imaging. *W.H. Rollins'* dental fluoroscope has been mentioned above (Fig. 8); *W.J. Morton* also showed interest in this technique in his early work [18], predicting that it would eventually replace

the use of still images, as it could speed up the examination by avoiding exposures of several minutes as well as film processing. The technique was abandoned rather quickly, however, due to its unjustifiable high radiation exposure as well as the relatively poor image quality. In 1908, a medical doctor named *G.E. Pfahler* made a strong statement in *Dental Cosmos*, claiming that the fluoroscope had no place in dentistry [43]. Later attempts to revive this technology (Fig. 14) were quelled. Whereas fluoroscopy is commonly used in contemporary interventional radiology, its use in dentistry has waned: the closest thing to ‘interventional’ dental radiography involves static images (*i.e.* periapical radiographs) acquired during different phases of root canal treatment.



Fig. 14 Top left: the Dentoscope, an intra-oral fluoroscope produced in Switzerland (ca. 1930s). Bottom left: the Indian Head X-ray Reflector of the Union Broach Company (US, ca. 1955). Distribution was halted by the State of New York. Pictures and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [44,45].

VI. EVOLUTION OF DENTAL (INTRA-ORAL) X-RAY UNITS

After the initial wave of dental radiographs produced in 1896 within weeks of Röntgen’s publication, one would expect rapid adoption of this new technology in routine dental practice. However, commercialization and widespread clinical implementation took quite some time. In 1905, the first dental X-ray machines were manufactured in Germany by the company now known as Siemens. In 1910 it was reported that only a few dentists in the USA used radiography, but in 1912-1913 dental X-ray units reached the US. In 1932, a survey by the American Dental Association showed that nearly half of newly graduated dentists procured an X-ray unit for their office.

One of the main reasons why so many researchers started experimenting with X-rays in early 1896 was the accessibility to the tools used by W. Röntgen and his predecessors. No new equipment or machines needed to be produced; one simply required an induction coil coupled to a Crookes-Hittorf (or similar vacuum) tube to generate X-rays. Both tools could be purchased or borrowed from physics labs, as they were commonly used for energy-based experiments. The reason why the Crookes-Hittorf tube was well-suited for X-ray generation is attributed to its relatively high vacuum. The dispersion of the remaining air molecules in the tube resulted in a constant electron stream; W.H. Rollins reported that high vacuum tubes resulted in increased radiographic detail [46]. Early improvements to the basic Crookes-Hittorf tube were implemented by König (see above). F. Harrison (UK) has been credited for designed a custom vacuum tube for dental radiography in January 1896 [16]. C.E. Kells also showed interested in the optimization of the technology used for generating X-rays at that time. In an 1899 paper published in *Dental Cosmos* [47], he evaluated the state-of-the-art in radiographic technology. Out of different available vacuum tubes, he found that the Crookes-Hittorf type was preferred. He also noted that the Tesla coil or the static (friction-based) Ranney-Wimshurst-Holtz machine were adequate substitutes of the Ruhmkorff coil, although a report of the US military showed preference for the latter due to its ease of use and lower bulk [48], both of which are relevant in a dental clinical environment as well.

A limitation of the Crookes-Hittorf tube set-up was a lack of consistency in the quantity and quality of X-rays. *George M. Mackee* and *John Remer* addressed this issue by proposing the use of a ‘radiochromometer’ that could measure the hardness of the X-ray beam, and a radiometer to measure the tube output [49].

Subsequent changes to the X-ray tube design, culminating in the Coolidge-type tube, which is still used today, are described in a prior paper [2]. In summary, in 1913, *William David Coolidge* (General Electric Co. New York) designed a tube in which a heated tungsten wire (cathode) served as the source of electrons, rather than residual air molecules in the vacuum. The new design improved safety as well as a more controlled X-ray quantity and quality. Furthermore, he discovered the dual purpose of oil immersion for electrical insulation and cooling. An adapted Coolidge tube for dental radiography was developed several years later. The following figures show the evolution of dental x-ray tubes throughout the decades (Fig. 15-29).

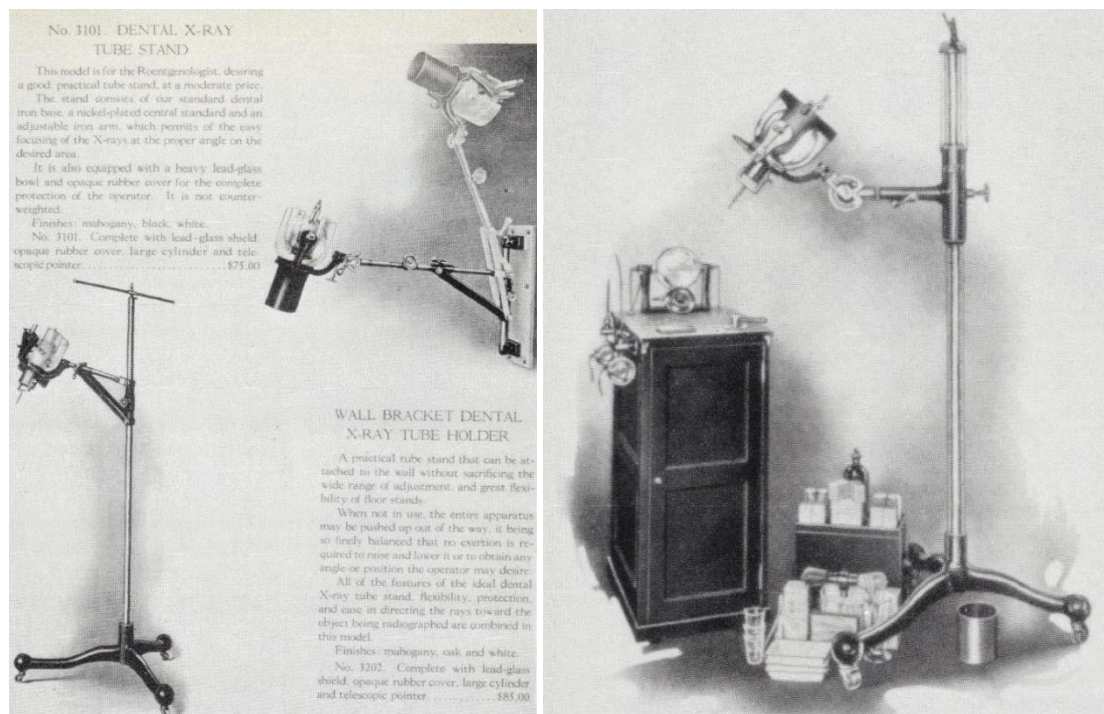


Fig. 15 Left: 1917 brochure for X-ray tube stand and wall brackets, used to adapt medical X-ray units for dental radiography. Multi-jointed arms of current intra-oral X-ray tubes were still years removed. Instead, the tube was stationary, and the patient was adjusted accordingly. Right: first commercial X-ray unit in the US (1913), produced by American X-ray Equipment Co. This unit used an induction coil, and was suited for AC or DC input, with exposures times of 10-20 s. The tube was shielded using lead glass [52].

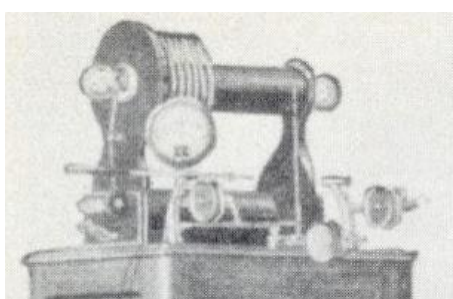


Fig. 16 Component of a "therapeutic" X-ray unit. Ca. 1914, the use of X-rays in combination with high-frequency current was being considered e.g. for periodontal treatment [52]. The application of this technique was short-lived.



Fig. 17 Coolidge-tube (10 mA), ca. 1922. Courtesy of D. Bednarek (University at Buffalo).

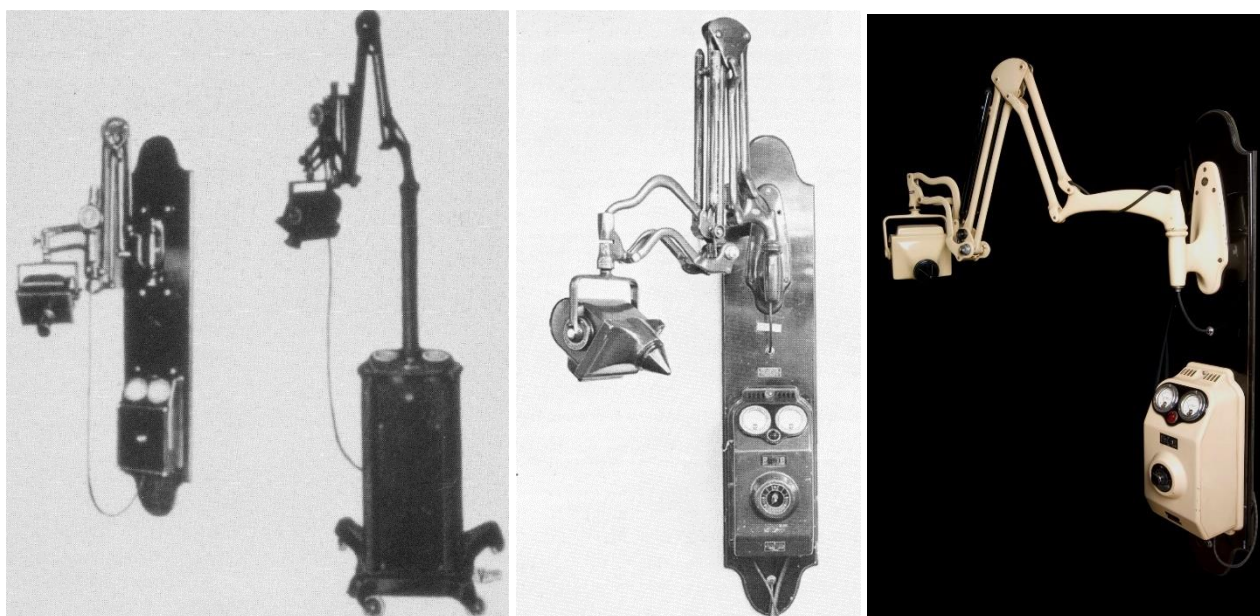


Fig. 18 Wall-mounted (left) and mobile (middle) 'CDX' Coolidge-type dental X-ray units (1923, Victor X-ray Corp., later General Electric X-ray Corp.). These units were shock-proof by collecting high-tension components within a grounded housing. Their compact design was possible owing to using smaller transformers as well as an autotransformer (vs. a rheostat) [52]. In 1933, the redesigned CDX model E (middle & right) was released, showing the typical closed 'pointed cone' position indicating device that would be used for several decades (*i.e.* the era of 'short cone bisecting-angle' intra-oral radiography). The unit shown on the right was still operational in 1981 (Science Museum Group under CC BY-NC-SA 4.0) [53].



Fig. 19 Coolidge-type RD (Radiator Dental) dental x-ray tube (Victor X-Ray Corporation), manufactured ca. 1926-1932. The right-angled design was suited for dental radiography, allowing close tube positioning. The cathode, which was closest to the patient, was grounded, and the high-potential anode was deliberately positioned away from the patient, according to the original 1919 patent [54]. Left: the spherical part of the tube shows the focusing cup and the target (embedded in a slanted copper block). Right: close-up of the focusing cup, showing the tungsten filament. When in use, a finned metal radiator was placed over the copper rod for heat dissipation (not shown on figure). This type of tube was self-rectifying, meaning that it could be directly attached to an induction coil or transformer. Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [55].

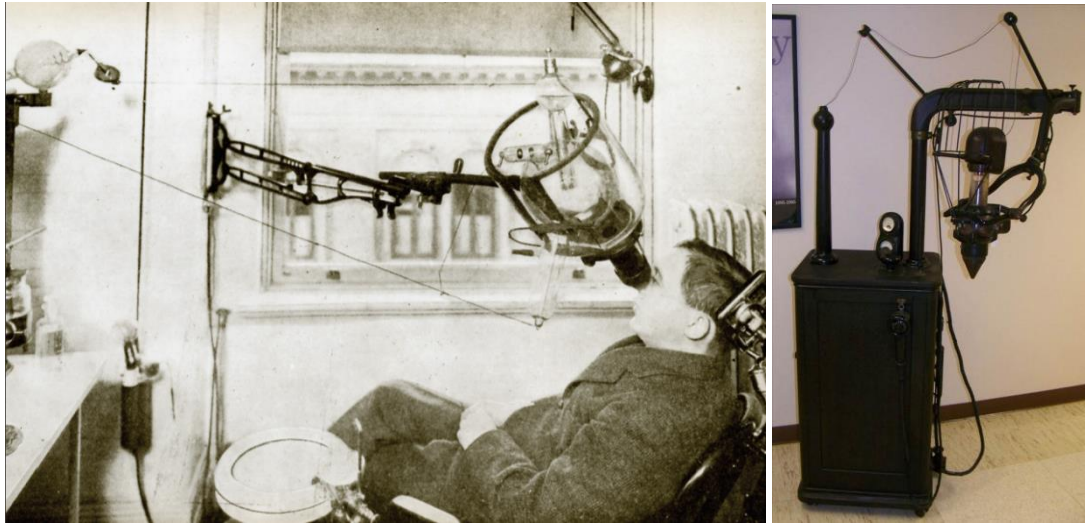


Fig. 20 Left: early X-ray unit with exposed high-tension wire, which is believed to have several grave (even fatal) accidents [52]. Right: the Ritter dental X-ray unit (1928), despite using a Coolidge tube, still had an exposed wire. Open-tube units were manufactured until the 1930s. Courtesy of D. Bednarek (University at Buffalo) [56].

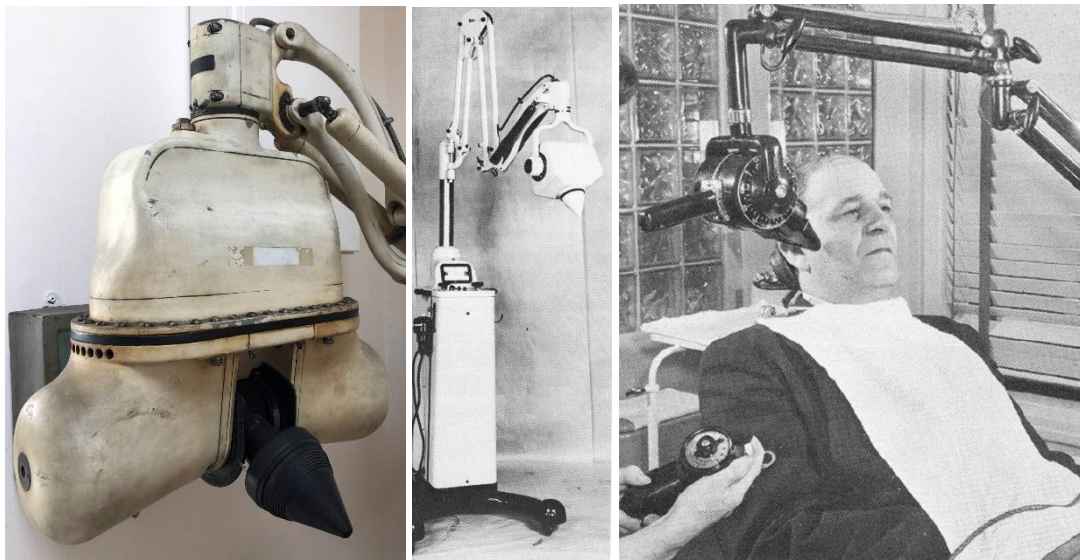


Fig. 21 Left: Ritter X-ray unit. Courtesy of P. Pittayapat (Chulalongkorn University). Middle: Weber no. 5 Raydex mobile dental X-ray unit, with a design typical of the late 1930s and 1940s. Right: the compact design of the Philips Oralix X-ray unit (1940s-1950s) allowed it to be attached to the dental chair; it was also produced as a wall-mounted or mobile unit [52].



Fig. 22 Top. Single focus dental XPD Coolidge tube (General Electric, ca. 1930s-1940s). Bottom: shock-proof dental x-ray tube (likely by General Electric, ca. 1935) [57]. The housing is made of several lead layers, separated by an insulating material. Figures and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [58,59].

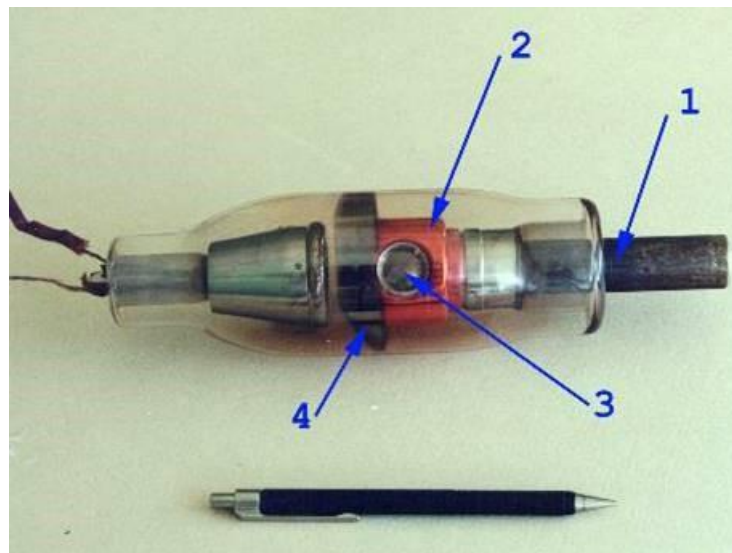


Fig. 23 X-ray tube with static anode (low power). 1. Anode stem. 2. Electron capture hood. 3. Beryllium window over the Anode. 4. Metallization of the glass envelope. Courtesy of S. Tabakov (King's College London).



Fig. 24 Ritter Dual-X unit (ca. 1950). Notice the double-cone design of the tube head, combining a longer source-skin distance with a position indicating device. Courtesy of P. Pittayapat (Chulalongkorn University).

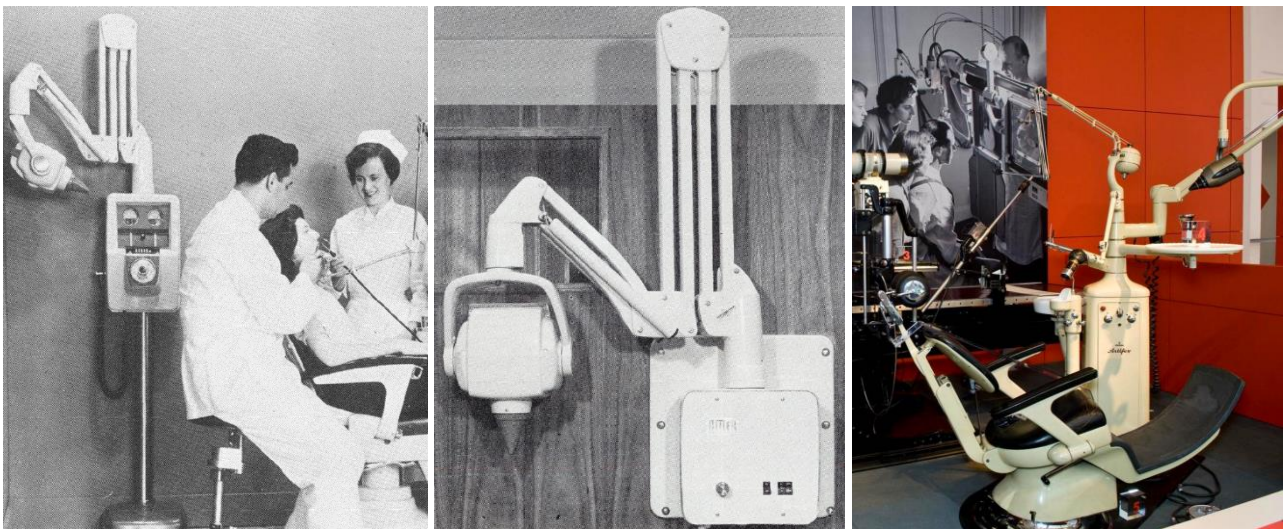


Fig. 25 Left: Ritter Model E X-ray unit (1956), with kilovoltages from 65 to 90 kVp. Throughout the 1950s, innovation to X-ray units included electronic timers, beam collimation and filtration [52]. Middle: Ritter Mark 75 model H (1966). This unit had preset mA and kV. Right: Heliodent X-ray machine (1957-1962) attached to an Artiflex dental unit (Siemens, Germany) (Science Museum Group under CC BY-NC-SA 4.0) [60].



Fig. 26 MAX-GL dental X-ray unit (South Korea, ca. 1972) with built-in chair. Courtesy of P. Pittayapat (Chulalongkorn University).

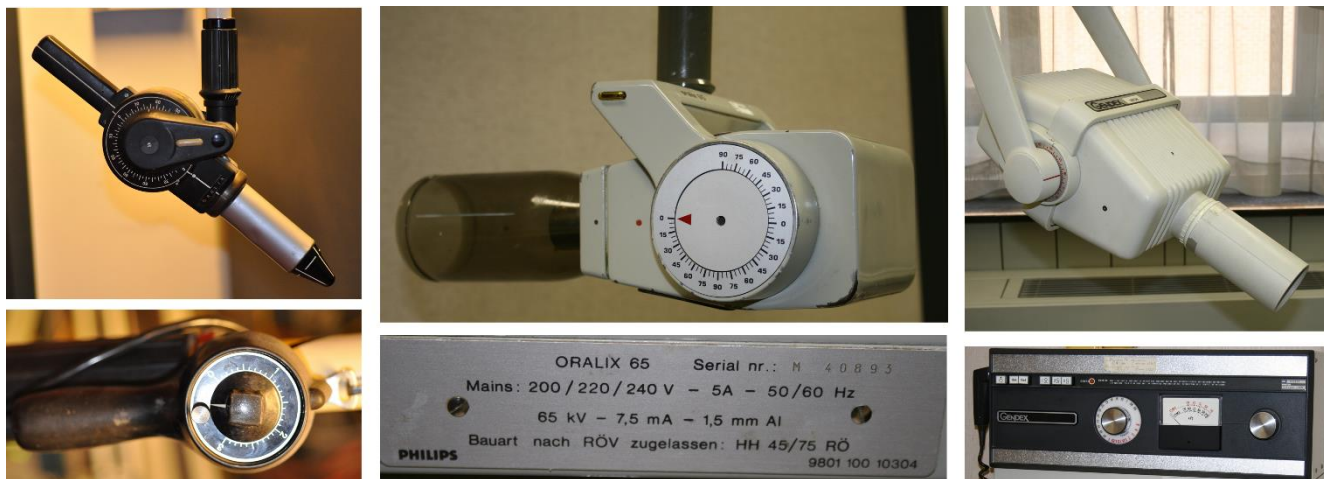


Fig. 27 Oralix 50 (left; ca. 1960s-1970s) and Oralix 65 (right; ca. 1984) intra-oral X-ray units (Philips, The Netherlands). The model number seemingly referred to the kV at stability (*i.e.* not the kVp) of the tube [61]; a ‘45’ model was also produced. Absorbed dose to the skin inside the primary beam ranged between 3.3 mGy and 9.7 mGy for these two units [61]. Right: Gendex GX 1000 (ca. late 1980s). Courtesy of J.K.M. Aps (University of Western Australia).



Fig. 28 Left: the MINRAY (1982-1992, Soredex, Tuusula, Finland), a high-frequency DC intra-oral X-ray unit. Courtesy of Soredex Oy and Dr Jörg Mudrak. Right: The MAX-F (1985, J. Morita, Kyoto, Japan), using a straight-cylindrical tube exit. Courtesy of J Morita.



Fig. 29 Intra-oral X-ray tube with circular (left, ca. 2005) and rectangular (right) collimation. The use of circular collimation is still prevalent, despite the considerable dose reduction obtained using rectangular collimation [61-64]. Right figure courtesy of K. Horner (University of Manchester)

The use of *hand-held (portable) X-ray units* for intra-oral radiography was first described in 1993, when the commercially developed PXS7 (Kevex X-Ray Corporation, USA) unit, with intended applications ranging from contraband/drug inspection to quality control in manufacturing, was compared with a conventional X-ray machine. In the following years, the interest in hand-held units increased in forensic [65] and clinical dentistry (Fig. 30). The main limitation of this technology is the proximity of the operator, resulting in exposure to scatter radiation. Furthermore, it was found that several hand-held units exhibited a low tube output, requiring a longer exposure time. Thus, it was recommended that they should only be used in specific environments, including but not limited to remote areas and facilities with immobile or confined patients (*e.g.* elderly homes and detention centers), and only if a mobile unit is not available [66,67].



Fig. 30 Portable hand-held intra-oral units. Reproduced from Pittayapat et al. 2012 [65] with the author’s permission.

VII. EVOLUTION OF DENTAL (INTRA-ORAL) X-RAY IMAGE RECEPTORS – FROM PLATE TO PLATE

A. Film

Several practical difficulties were found in the early implementation of dental radiographs. To produce dental radiographs the photographic glass plates had to be cut in small pieces, wrapped in lightproof paper, and placed in a rubber dam [68]. Due to the extremely long exposure time as well as the weight and bulk of the plates, it was reported to be a quite uncomfortable experience by O. Walkhoff himself:

“It was a true torture, but I felt a great joy at the sight of the results when I become aware of the importance of the Röntgen rays for dentistry.” (O. Walkhoff, as quoted by Forrai [11])

The fragility and the cost of the plates was another issue to consider. W. Röntgen himself remarked that film can be used instead of glass plates [69]. Initially, Eastman NC films were meticulously cut and wrapped in black paper. Early use of film in dental radiography was challenging due to stability issues as well as the necessity to maintain the film dry. Morton proposed the use of gutta percha receptacles to avoid that the emulsion became wet [18].

The following timeline (Table 1) and figures (Fig. 31-35) show the evolution of dental X-ray film throughout the years, as described by Campbell [70] and other reviews.

Table 1 Evolution of dental X-ray film, starting with initial commercialization

Year	
1913	The first commercial, hand-wrapped dental x-ray film was marketed by Kodak, comprising a waxed, water-proof paper packet and two single-emulsion films.
1919	A film with a cellulose nitrate base allows for the exposure of a molar in 9 s. The film was highly flammable, however, and burning would release poisonous gases [70].
1921	Machine-made dental film packets were produced.
1924/1925	Radiatized fine-grain dental film with a double-sided emulsion and a non-flammable cellulose triacetate base was introduced, doubling the film speed and avoiding curling of the film.
1941	Ultraspeed film reached the market, again doubling the speed of radiatized film.
1955	D-speed film was introduced with an increased graininess, showing an 8 to 20 times higher speed than original film.
1960	A stronger, polyester (Polyethylene terephthalate a.k.a. Dacron) film base was developed
1967	Polysoft water-proof dental film packets were introduced for enhanced comfort
1981	E-speed (Ektaspeed) film was introduced, showing an approximately two times higher speed as D-speed film at the cost of reduced film contrast. Clinical acceptance was further limited due to its sensitivity to long-term storage [71].
1994	Kodak Ektaspeed Plus film becomes available, with flattened silver halide crystals (T-Mat emulsion) rather than traditional pebble-shaped grains, resulting in improved resolution at a relatively high speed. The dose reduction from D-speed to E-speed was reported to be 30-40%
2000	F-speed film became available in 2000 (Kodak/Carestream Dental Insight), using the same emulsion as E-Plus but with an optimized silver grain distribution (T-Grain), allowing for the exposure to be further reduced by 20-25% [71].



Fig. 31 Left: Eastman (Kodak) radiatized dental film. Right: Victor-Bolin dental film container (ca. 1930; patent by Bolin granted in 1925 [72]). Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [73].



Fig. 32 Wolf X-ray intra-oral cassette for occlusal radiography (ca. 6.4 x 8.3 cm). The cassette appeared in a 1955 catalog, which mentioned an exposure time of 1.5-2 s. Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [74].



Fig. 33 Dental film holders (ca. 1937). The text on the box reads "The wood block film holder is used to radiograph films in the mouth, especially where it is difficult for patient to hold the film in proper position or when patient is distressed by film. Insert film, folded side against rounded part of the block, and have patient bite on adjoining flat surface. Can be used either upper or lower." One block is approx. 1.8 cm across. A box of 10 blocks sold for \$0.25 [75]. Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [76].



Fig. 34 'Sta-put' bitewing tabs and Minimax bitewing film packets. Courtesy of D. Bednarek (University at Buffalo).

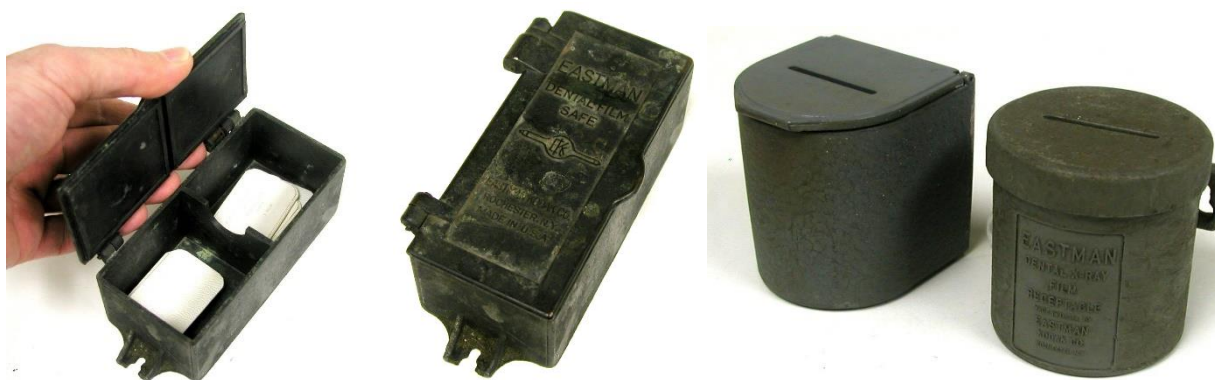


Fig. 35 Wall-mounted shielded X-ray film containers for storing film prior to development. Left: Eastman Dental Film Safe (1920s), with two compartments for a total of 24 film packets. Right: more recent units by Eastman/Kodak; the rightmost is shown in a 1955 catalog. All containers seem to be made of a lead alloy. Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [77].

The *development process* of plates and film was based on previously established concepts in photography. The importance of this aspect of radiography may have been underestimated during the early years. In a 1922 paper, C.E. Kells reviewed the significance of proper film development, emphasizing that radiographic image quality is as affected by the operator's expertise as the X-ray exposure itself [78]. He also focused on the importance of having constant environmental factors (*e.g.* temperature). An automatic developer was introduced early-on, with the dual benefit of reducing operator-dependency and saving time; regardless, manual film development is still performed to this day (Fig. 36-39).



Fig. 36 Left: A dental assistant (hygienist) developing an X-ray film (original source and year unknown). Middle and right: automatic processors for intra-oral films and large films. Courtesy of A. Al-Ekrish (King Saud University).



Fig. 37 Left: Litton automatic dental film processor with daylight loading. Courtesy of D. Bednarek (University at Buffalo). Right: Manual development using a lightproof glovebox.



Fig. 38 Left: Safelight filter for intra-oral films. Middle: Kodak dental film dispenser. Courtesy of S. Anamali (University of Iowa). Right: Rinn dental film dispenser. Courtesy of D. Bednarek (University at Buffalo).



Fig. 39 Left: Digital densitometer (DD500 S&S X-Ray Products). Right: troubleshooting guide for dark and light radiographs. Courtesy of S. Anamali (University of Iowa).

B. Digital receptors

The transition to digital dental radiography was gradual [79] and is still on-going. In 1987, a digital *charge-coupled device* (CCD) intra-oral detector was introduced (RadioVisioGraphy, Trophy Radiologic, France; Fig. 40) [80]. The advantages of reduced patient exposure and immediate availability of the image were immediately apparent, although the spatial resolution was less than that of film [79]. Further improvements to CCD-based sensors were made in the following years. *Photostimulable phosphor* (PSP) receptors were introduced in 1994 (DIGORA, Soredex, Finland; Fig. 40)) despite having been used in medicine as early as 1983. Whereas resolution was considered somewhat inferior to CCD systems, PSPs showed an improved dynamic range [81,82] and signal-to-noise ratio [83]. *Complementary metal-oxide semiconductor* (CMOS) sensors were commercialized in 1998 (CDR-APS, Schick Technologies, USA) and have largely replaced CCD sensors in intra-oral radiography owing to several advantages such as cost, dynamic range and the absence of blooming/smearing effects [79]. In a 2001 survey involving Norwegian dentists, two thirds of the respondents found that digital (solid state sensors or PSP) receptors yielded equal or better image quality than film, at a mean reduction in exposure time of 55% [84]. Furthermore, the use of digital receptors saved an average of 36 min/day and 25 min/day for sensors and PSPs, respectively. A dosimetric study published in 2008, using the latest tissue weighting factors from the International Commission on Radiological Protection [85], found a 56% effective dose reduction for PSPs or F-speed film vs. D-speed film [86]. A more detailed overview digital receptors in intra-oral radiography, including their performance vs. film, can be found in the review by Yoshida et al [79].



Fig. 40 Left: the RadioVisioGraphy a digital charge-coupled device (CCD) intra-oral detector (1987, Trophy Radiologic, France). Courtesy of A. Wenzel, Aarhus University. Right: The DIGORA ('DIGitalORAI') system intraoral imaging system using storage phosphor plates (1994, Soredex, Tuusula, Finland). Courtesy of Soredex Oy and J. Mudrak.

C. Xeroradiography

Xeroradiography was invented by the American physicist and patent attorney *F. Chester Carlson*, aided by *Otto Kornei*, in 1937. Ten years later, the Haloid Company (later known as Xerox) started commercial development. The technique was used in several areas of medicine and was first used for dental radiography in 1963 [87]. It was applied for panoramic and cephalometric radiography as well as sialography [88]. In 1978, intraoral xeroradiography was introduced and evaluated for endodontic use; it was found to depict anatomical structures more clearly than film radiographs at a third of the dose, along with a rapid image generation (20 s after exposure) [89]. Xeroradiography is performed using a plate containing a 150-320 μm amorphous selenium layer and a 2 mm thick aluminum substrate. Prior to X-ray exposure, a uniform positive charge is applied to the plate surface using a 'scorotron' [90]. If used intra-orally, the cassette is covered by plastic to avoid contact with saliva. When the surface is exposed with X-rays, the charge will be passed to the grounded conductive backing in proportion with the exposure, resulting in a latent image. Development involves electrophoresis with a negatively charged (powder or liquid) toner, which is (1) deposited on the photoconductor, (2) attaches itself to the remaining negatively charged areas, and (3) is transferred and fixed to a paper or plastic sheet. After cleaning the plate, it can be reused. Advantages of the technique include a low sensitivity to ambient light, high resolution, high dynamic range, low cost, straightforward copying of radiographs, and high (development) speed. On the other hand, contradictory reports regarding the relative dose of xeroradiography vs. film radiography can be found [91-93]. Xeroradiography gained interest for use in endodontics, as its contrast in the soft tissue density range allowed the visualization of calcification in the pulp and its spatial resolution allowed the depiction of fine anatomical details as well as instruments. However, several disadvantages of the technique became apparent, such as the impracticality of using charged plates intra-orally due to the presence of saliva. Furthermore, the 'speed' of the system was proportionate to its thickness, which in turn was limited by the space in the oral

cavity. The surface of the plate was also rather fragile. The technique has since faded from clinical dental use, despite calls for its reintroduction [94].

VIII. HISTORY OF PANORAMIC RADIOGRAPHY

Panoramic radiographic is a unique imaging modality, specifically designed for dental applications. The challenge addressed by this technology was to acquire a single radiograph that encompassed all teeth of the upper and lower jaw. The invention of the panoramic radiography unit is largely attributed to *Yrjö Paatero* [95], a Finnish dentist whose work resulted in widespread clinical practice and commercial distribution after the second World War (Fig. 41). However, the technique itself is much older; in 1922, Zulauf (USA) proposed a narrow-beam scanning technique for upper and lower jaw, obtaining a patent [96]. He also coined the term ‘panoramic radiography’. Numata (Japan) published clinical results of a prototype ‘parabolic radiography’ device in 1933 [97]. Heckmann (Germany) obtained a patent for narrow-beam radiography of curved objects in 1939 [98].

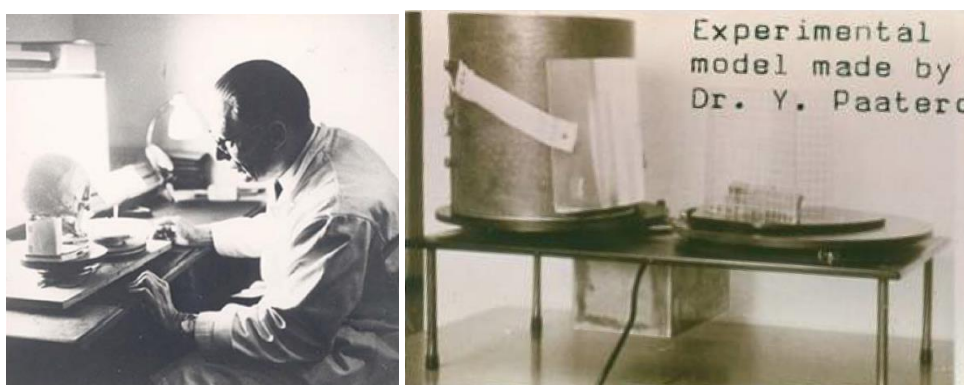


Fig. 41 Yrjö Paatero and one of his early experimental set-ups. Courtesy of Instrumentarium Oy and J. Mudrak.

After the second World War, Paatero took up a position at the Institute of Dentistry of the University of Helsinki and was seemingly pushed into taking charge (and becoming the only member) of the Department of Radiology. Despite a high clinical workload and scarce resources, Paatero was able to make important contributions to the field. It has been speculated that one of the driving forces behind Paatero’s dedication was the unsustainable work pressure in his one-man department; indeed, the workflow in dental radiography could be sped up considerably by replacing several radiographic acquisitions by a single panoramic radiograph. His work progressed quickly, despite being unaware of previous publications and patents on this technique: in 1946, a preliminary report was published in the Proceedings of the Finnish Dental Society. Initially, he used a long, curved film placed intra-orally, exposed with a moving narrow X-ray beam that passed along the patient’s face. The resulting image was dubbed ‘parablograph’ in 1949. In the same year, Paatero altered this technique by placing the film extraorally (curved around the face) and having a relative rotation of the X-ray tube posterior to the patient (Fig. 42). Paatero referred to this technique as the orthoradial pantomograph, eventually shortened into the trade name ‘Orthopantomograph’, which is still used as a generic term for panoramic radiography, along with its abbreviation ‘OPG’. Whereas the X-ray tube was stationary in early iterations, eventually prototypes were constructed in which the tube rotated.

An important step towards eventual commercialization of this technique was made in the early 1950s, when Paatero liaised with an engineer named *Timo Nieminen* via the Finnish company *Lääkintäsähkö*. The two would closely collaborate for the next decade. Paatero also spent a few years at the University of Washington, contributing to the development of a double eccentric rotation technique that was later patented by Hudson et al. (USA) [99]. After returning to Finland, Paatero and Nieminen developed a panoramic radiography unit with a triple rotation center [100], followed by extensive clinical testing [101-105] (Fig. 42).

Through collaboration with Siemens, who produced the X-ray tube and generators, the commercialization of the Orthopantomograph commenced in 1960 (Fig. 43-44). In 1965, the company Palomex (Panoramic Layer Observing Machine for Export) was established. In the USA, after clinical testing of the double eccentric machine of Hudson et al., production of the ‘Panorex’ commenced by the S.S. White company (Pennwalt Corporation). In the UK, after gaining expertise with a panoramic radiography unit produced in Helsinki, S. Blackman worked with the company Watson & Sons in the development of a panoramic machine named the Rotograph [106]. Soon enough, other manufacturers around the world produced panoramic radiography units (Fig. 45-55).

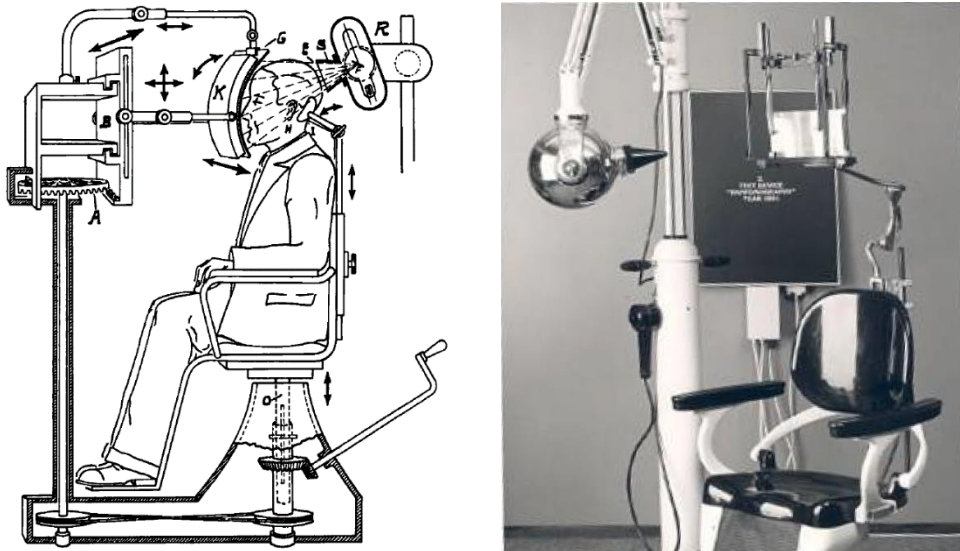


Fig. 42 Panoramic radiography applied in dental practice. Left: schematic (1949). Right: unit for clinical testing (1951). Courtesy of Instrumentarium Oy and J. Mudrak.

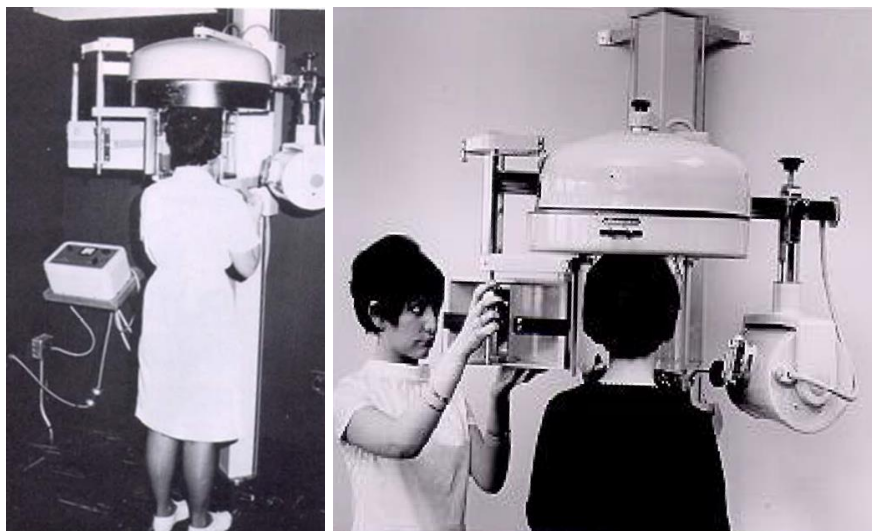


Fig. 43 The Orthopantomograph OP1 (1961-1964, Instrumentarium, Tuusula, Finland). Courtesy of Instrumentarium Oy and J. Mudrak.

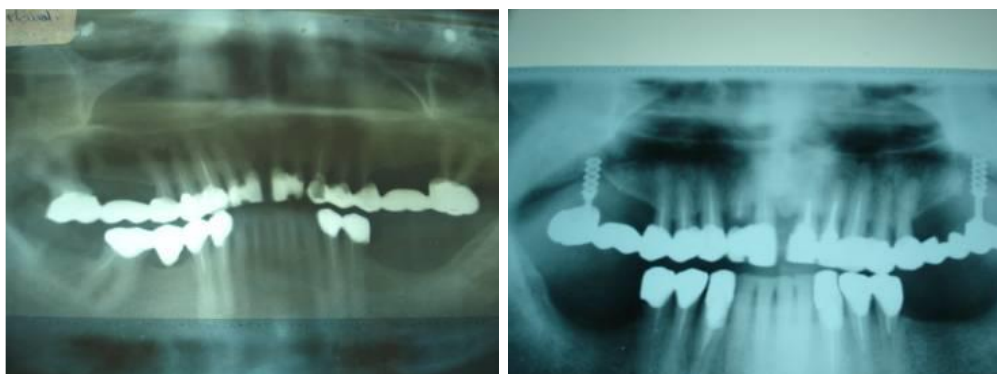


Fig. 44 Early use of panoramic radiographic for planning (left) and post-operative evaluation (right) of enossal (spiral) implants (1962). Courtesy of Instrumentarium Oy and J. Mudrak.

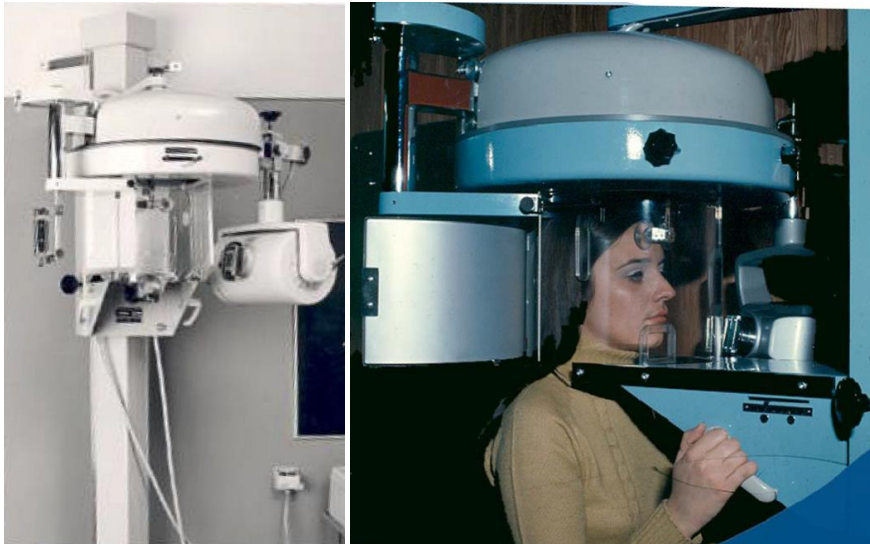


Fig. 45 The Orthopantomograph OP2 (1964-1972, Instrumentarium, Tuusula, Finland) featured an improved imaging geometry and a redesigned, curved cassette. Courtesy of Instrumentarium Oy and J. Mudrak.



Fig. 46 Left and middle: the Orthopantomograph OP3 (1972-1978, Instrumentarium, Tuusula, Finland) combined panoramic and cephalometric radiography. Over 10 000 units were produced. Right: the Orthopantomograph OP5 (1978-1983, Instrumentarium) featured new patient positioning tools and an improved imaging geometry. Over 20 000 units were produced. Courtesy of Instrumentarium Oy and J. Mudrak.



Fig. 47 The Orthopantomograph OP10 (1983-1984, Instrumentarium, Tuusula, Finland) implemented horizontal (Frankfort) positioning lights and advanced imaging programs. Courtesy of Instrumentarium Oy and J. Mudrak.



Fig. 48 Left: The Panex-E by (1972, J Morita, Kyoto, Japan). Middle: The Panex-EC panoramic/cephalometric unit (1975, J Morita). Right: the Veraview (1979, J Morita), brandishing an electronic control system. Courtesy of J Morita.

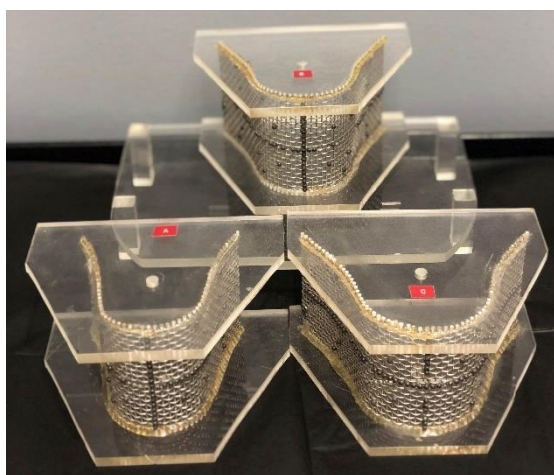


Fig. 49 Vintage calibration phantoms for panoramic radiography. Separate phantoms were used for small, medium and large jaws. Courtesy of S. Anamali (University of Iowa).

Further development of panoramic radiography was aided by its clinical implementation: whereas AC generators used in early models were often of the one-pulse type, the use of this modality in hospitals allowed them to be coupled to 12-pulse generators, which in turn allowed the use of rotating anode tubes [100]. DC generators were introduced by Soredex (Finland) in 1978.

A dosimetric study in 1979 found that the energy imparted in the head and neck from panoramic radiography was between 0.45 mJ and 4.5 mJ; for different combinations of conventional radiographs, the same range was found (*i.e.* from 0.40 mJ for left and right oblique, up to 4.4 mJ for full mouth series at 65 kV) [107]. The highest local absorbed dose was 3.7 mGy for panoramic radiography, whereas an absorbed dose at the corner of the mouth of 10 mGy and 12 mGy was measured for a full mouth series at 45 kV and 65 kV, respectively [107].

Mechanical movement was gradually replaced by step motors and electronic control systems. The ergonomics of the device was also improved through innovation in patient position devices. Whereas mechanical movement allowed for variations in exposure geometry for visualization of non-dental structures (*e.g.* optic foramina and cervical spine), further development initially focused on image layers that followed the dental arch, until electronics allowed for the customization and further refinement of image layers as described by Hallikainen (Fig. 50) [100].



Fig. 50 The Zonarc (Palomex Oy, Helsinki, Finland) unit allowed for the visualization of structures outside of the dental region. The patient is in a supine position, and the movement of the X-ray tube and receptor rotate in the vertical plane. Rotation of the tube/receptor was complemented by up/down movement of the unit to create eccentric motion paths [108]. Courtesy of J.K.M. Aps (University of Western Australia).



Fig. 51 Panoramic single-jaw radiograph with intra-oral X-ray source and extra-oral film, placed in a flexible cassette (top right), which was held by the patient wrapped around the face. The cross marker on the cassette faced the operator and served as a guide in determining the midsagittal plane. Maxillary views (left) were made with the patient in an upright position and the cassette placed above the tube. For mandibular views, the patient's head was slightly tilted back and they would bite on the X-ray tube. The tube was a small cylinder covered with a disposable sleeve. Courtesy of K. Sansare and F. Karjodkar (Nair Hospital Dental College).

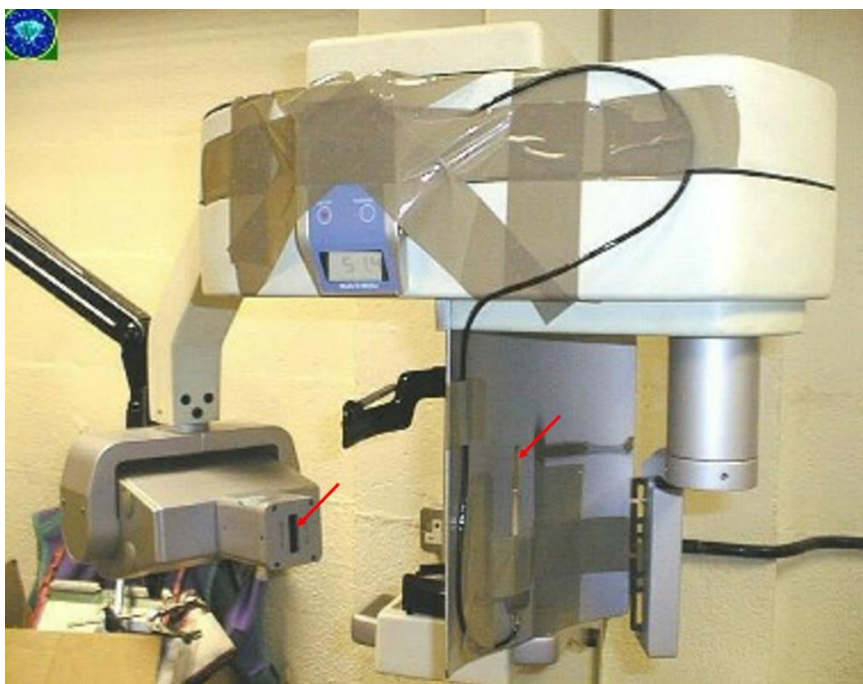


Fig. 52 Quality control on a film-based panoramic radiography unit (ca. 1990). The dosimeter was firmly affixed to the rotating assembly. Note the metals slits of the X-ray tube and of the film holder (marked with arrows). Courtesy of S. Tabakov (King's College London)

Along with the digitization of other radiographic techniques in dentistry and medicine, ‘computed’ panoramic radiography (Fig. 53-55) was developed in the 1980s, first described by Kashima et al. in 1985 [109]. Direct digital panoramic radiography followed in the early 1990s [110,111]. Some current-generation panoramic units have incorporated direct-conversion (CdTe) receptors. Recent dosimetric studies involving panoramic radiography are somewhat scarce. A 2019 study found an absorbed dose of 0.62 mGy for CCD panoramic radiography vs 0.80 mGy for intra-oral radiography [112]. One of the most recently reported effective dose values is 17.6 μ Sv for a full-size panoramic radiograph with a CCD detector, with dose reductions between 4.5% and 86.9% for collimated radiographs [113]. A 2008 study involving two CCD-type panoramic units found effective doses of 14-24 μ Sv [86]. A 2005 study, using now-outdated tissue weighting factors, found effective doses between 5-15 μ Sv for digital (CCD or PSP) panoramic radiography [114].



Fig. 53 The Orthopantomograph OP100 (1992-2006, Instrumentarium, Tuusula, Finland) implemented automatic exposure control, computed radiology (CR) and linear tomography (OrthoTrans). Courtesy of Instrumentarium Oy and J. Mudrak.



Fig. 54 The Orthopantomograph OP100D and two-in-one Orthoceph OC100D (1999-2006, Instrumentarium, Tuusula, Finland) had digital (charge-coupled device, CCD) image receptors. CCD image receptors were used as well in the OP30 model (2009). In the OP300 (2010), complementary metal-oxide-semiconductor (CMOS) digital sensors are used. Courtesy of Instrumentarium Oy and J. Mudrak.



Fig. 55 Left: Digital panoramic system 'Veraviewepocs' (1998, J Morita, Kyoto, Japan). Middle: Veraviewepocs 3D, a '3-in-1' (panoramic/cephalometric/cone-beam CT) system (2007, J Morita). Right: Veraview X800 (2016, J Morita) 3-in-1 unit. Courtesy of J Morita.

IX. OTHER EXTRAORAL RADIOGRAPHIC TECHNIQUES

The most common type of extra-oral, non-tomographic radiographic technique in dentistry is the lateral cephalometric radiograph. The posteroanterior cephalometric radiograph is used less frequently, *e.g.* for the evaluation of left-right symmetry. Other projections (Fig. 56-57) usually require isocentric (or formerly Lysholm) skull units and are not performed in a typical dental office; the most common techniques are shown in Fig 56.

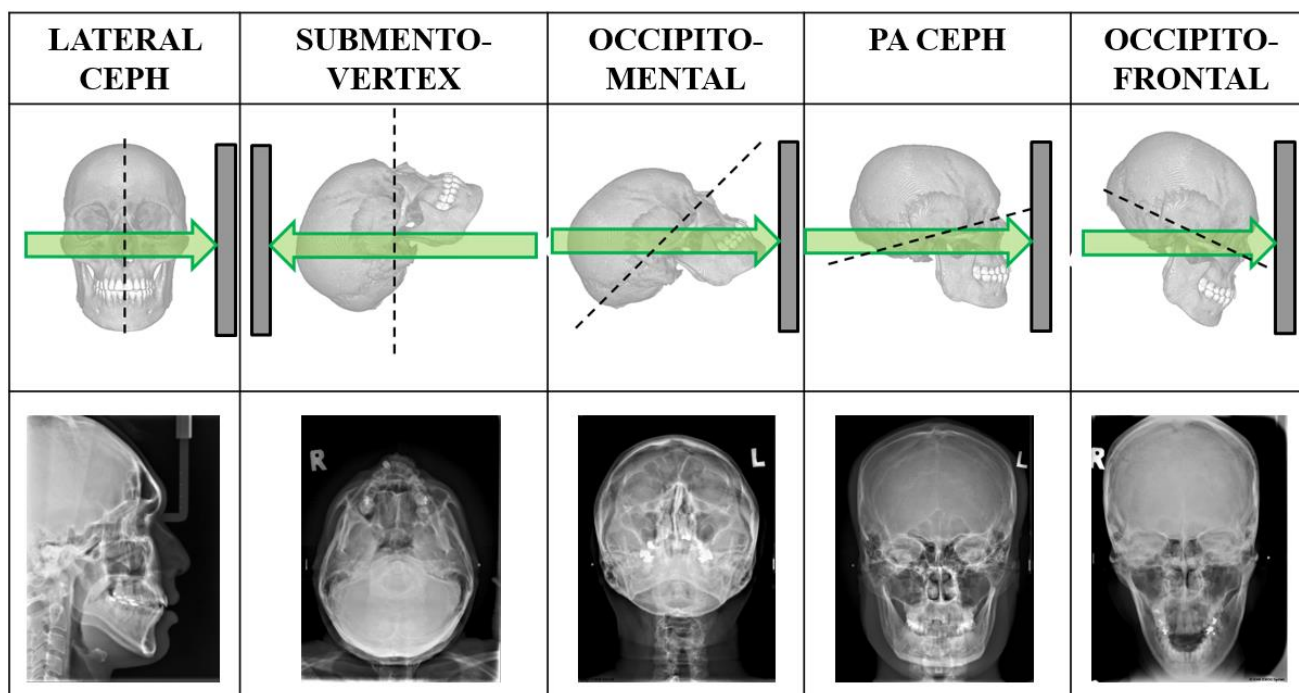


Fig. 56 Overview of common extra-oral projection radiography techniques. Own work, from the IAEA Training Material “Radiation Protection in Dental Radiology” [115]. Radiographs courtesy of P. Pittayapat, Chulalongkorn University, Bangkok, Thailand.



Fig. 57 Left and middle: transcranial radiograph in open and closed mouth position, indicating degenerative joint disease. Right: lateral oblique radiograph showing temporomandibular joint ankylosis. Courtesy of K. Sansare, Nair Hospital Dental College.

A. Cephalometric radiography

The origin of head measurements can be traced back to Leonardo da Vinci and other Renaissance scientists and artists. Facial proportions and angles were used in the next centuries for ethnic evaluation and the analysis of human remains, using the ‘cephalic index’. In 1931, the use of cephalometric analysis in orthodontics commenced [116,117]; the use of a cephalostat for standard head positioning allowed for the evaluation of normal/average cephalometric features [118]. After World War II, cephalometric radiography gained acceptance (Fig. 58-59), and several cephalometric analyses were defined, including those by Steiner (1953), Ricketts (1960) and McNamara (1983) (Fig. 60). Computerized cephalometrics, with a much-improved workflow due to the automatic calculation of distances and angles, was introduced in the late 1960s [119]. The evolution of image receptors in cephalometric radiography was concurrent with that of panoramic radiography, with the latest innovation being the use of direct-conversion CdTe sensors.



Fig. 58 Vintage cephalostat. Courtesy of A. Wenzel, Aarhus University

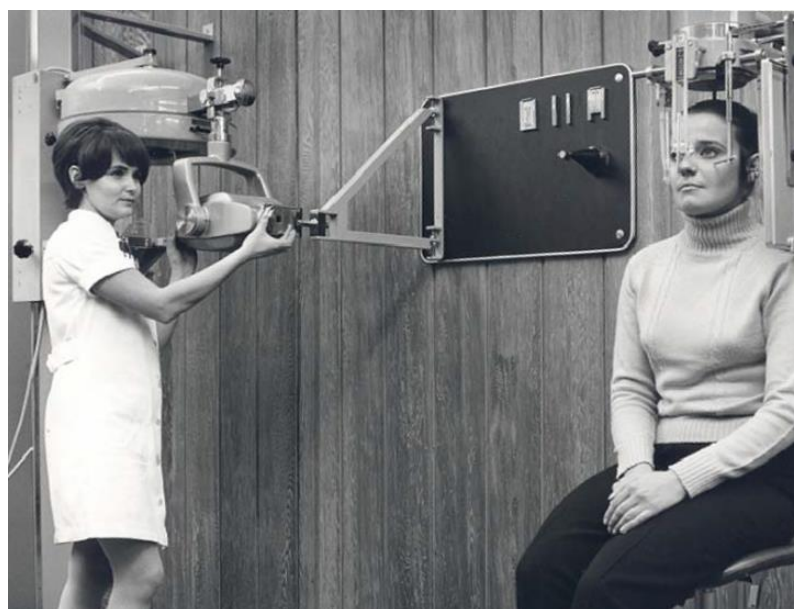


Fig. 59 Experimental cephalostat used with the Orthopantomograph OP1 panoramic radiography unit (Instrumentarium, Tuusula, Finland). Two-in-one panoramic/cephalometric units gained popularity in the 1970s with the introduction of the Orthopantomograph OP3 (Fig. 46). Courtesy of Instrumentarium Oy and J. Mudrak.

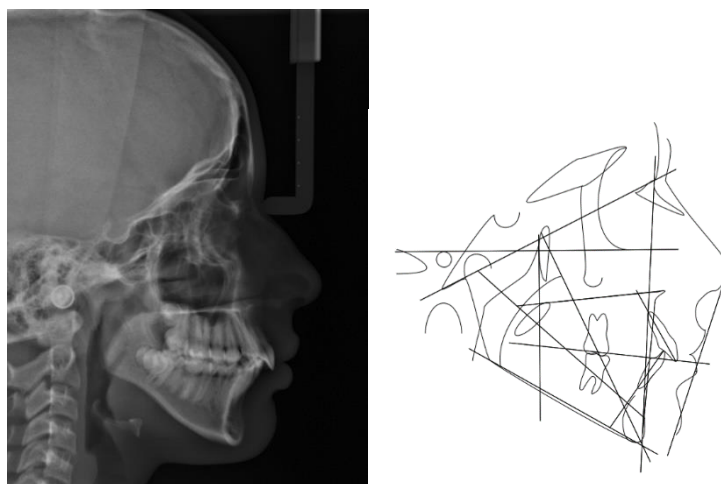


Fig. 60 Lateral cephalometric radiograph (left) and corresponding Ricketts cephalometric analysis (right). Courtesy of K.F. Vasconcelos (Catholic University of Leuven).

B. Sialography

Another type of radiography used in dentistry is sialography (Fig. 61), which originated in 1925 [120]. By injecting contrast medium (typically into a salivary gland, and acquiring an extra-oral radiograph, different types of pathosis could be evaluated, including tumors, duct obstruction (*e.g.* calculus), and inflammatory disorders such as Sjögren's syndrome [121]. The main reason why sialography had difficulty getting accepted in clinical practice was the rather impractical technique, with an excess of contrast medium (*i.e.* a type of iodobenzene known as Pantopaque/Myodil) resulting in both pain to the patient and impaired diagnostic efficacy. Whereas modified sialographic techniques were proposed [122,123], including the use of more suitable contrast media, catheters, and gland stimulation techniques, the advent of advanced imaging techniques (CT, MRI, ultrasound) [124] has rendered sialography largely obsolete.

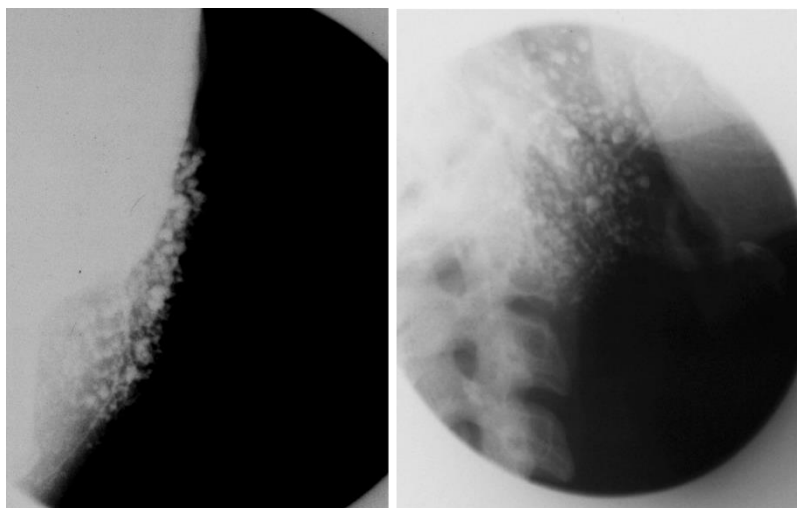


Fig. 61 Sialogram of the parotid gland. Courtesy of Asma'a Al-Ekrish, King Saud University, Riyadh, Saudi Arabia.

X. DENTAL TOMOGRAPHY

Panoramic radiography, discussed in the previous section, is in fact a special type of tomography in which a curved 'slice' is formed that follows the dental arch. Whereas panoramic radiography has remained a routine imaging technique in dentistry, other types of tomography were used for several years in dentistry but have faded from clinical use since the introduction of computed tomography.

The origin of tomography has been the source of debate [125], with claims of the invention coming from Netherlands, France, Italy, USA, and Germany. The theoretical aspects were described in the late 1910s, but the first experimental units were produced around 1930. The problem that was addressed by tomography was the same reason radiostereoscopy was

developed (Section V), *i.e.* overcoming superimposition of anatomical structures to reveal hidden pathosis. The solution offered by tomography was the use of a moving X-ray source and receptor. The movement is controlled in a way that points within a plane of interesting (*i.e.* the section plane) are always projected on the same part of the receptor, appearing sharp on the tomogram (Fig. 62-65). Conversely, points outside the section plane are projected differently on the receptor throughout the motion and are thus blurred, with the degree of blurring determined by the distance to the section plane. The location of the section plane can be altered either by changing the fulcrum of the tube/receptor movement or by adjusting the position of the patient. The thickness of the slice is inversely correlated to the distance of the tube movement. In the 1980s, dedicated dental tomographic units were developed with a spiral motion path (not to be confused with the misnomer ‘spiral CT’, which refers to a different modality altogether) (Fig. 62, Fig. 66).

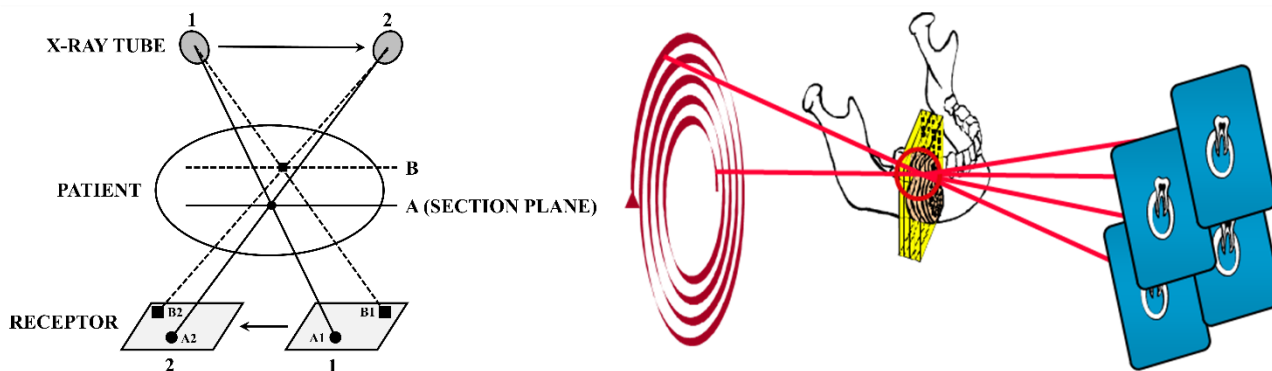


Fig. 62 Left: principle of tomography. The section plane (A) is determined by the relative position and motion of the X-ray tube, patient and receptor. Points outside the section plane (B) are projected on different areas of the receptor throughout the motion, and appear blurred, whereas points within the section plane appear sharp. Right: tomography using a spiral motion path, popularized in dentistry in the late 1980s [126]. Right figure courtesy of Soredex Oy and J. Mudrak.

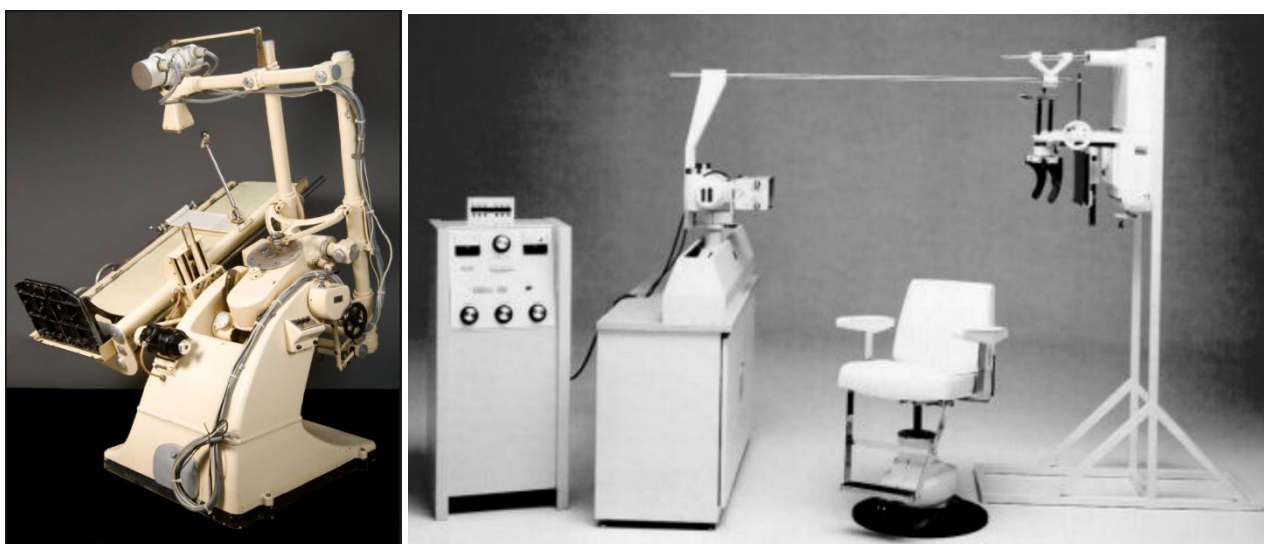


Fig. 63 Left: Polytome universal tomograph (Philips Medical Systems, 1950s). Right: Quint Sectograph (USA) used from the 1960s onward. In dentistry, this unit could be used for cephalometric imaging and, using its linear tomographic function, for imaging of the temporomandibular joint. The tube would move along the slot shown on the left side, and a metal rod ensured reciprocal movement of the image receptor. A grid was typically used. Information provided by Stuart White, University of California, Los Angeles. Left figure obtained from Science Museum Group under CC BY-NC-SA 4.0 [127]. Right figure retrieved from www.dotmed.com, original source unknown.

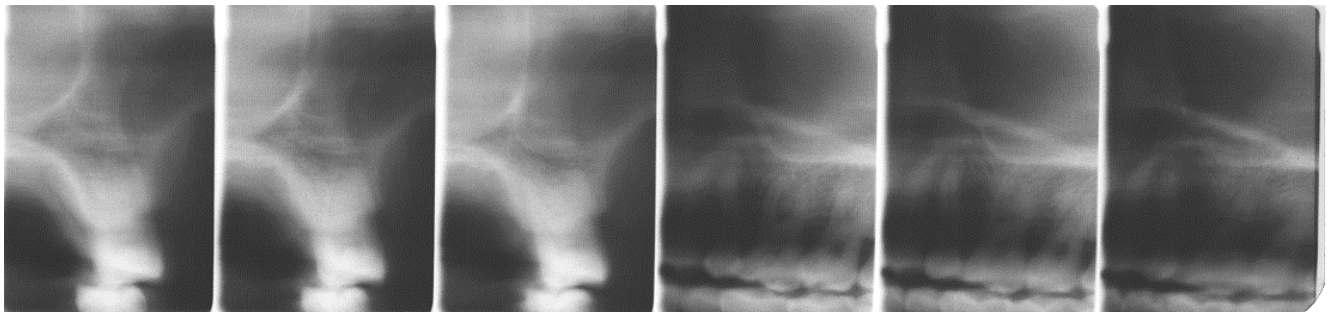


Fig. 64 Tomographic images of Orthopantomograph OP100 (Instrumentarium, Tuusula, Finland). Orthogonal views are generated from distal to mesial (left half of figure) and from buccal to palatal (right half of figure). Courtesy of Instrumentarium Oy and J. Mudrak.

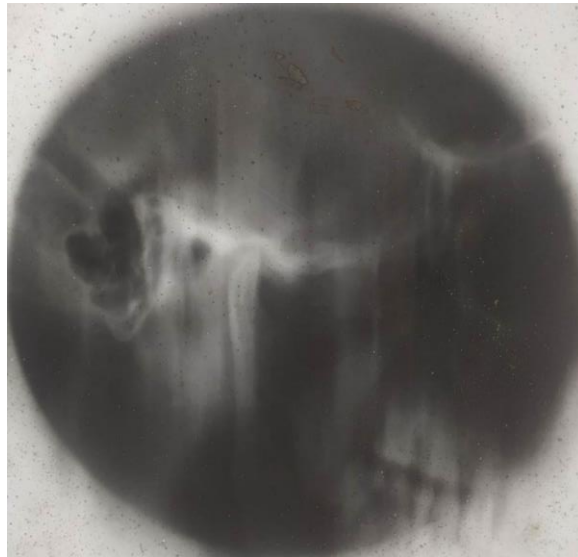


Fig. 65 Tomogram of the temporomandibular joint. Courtesy of K. Sansare (Nair Hospital Dental College).

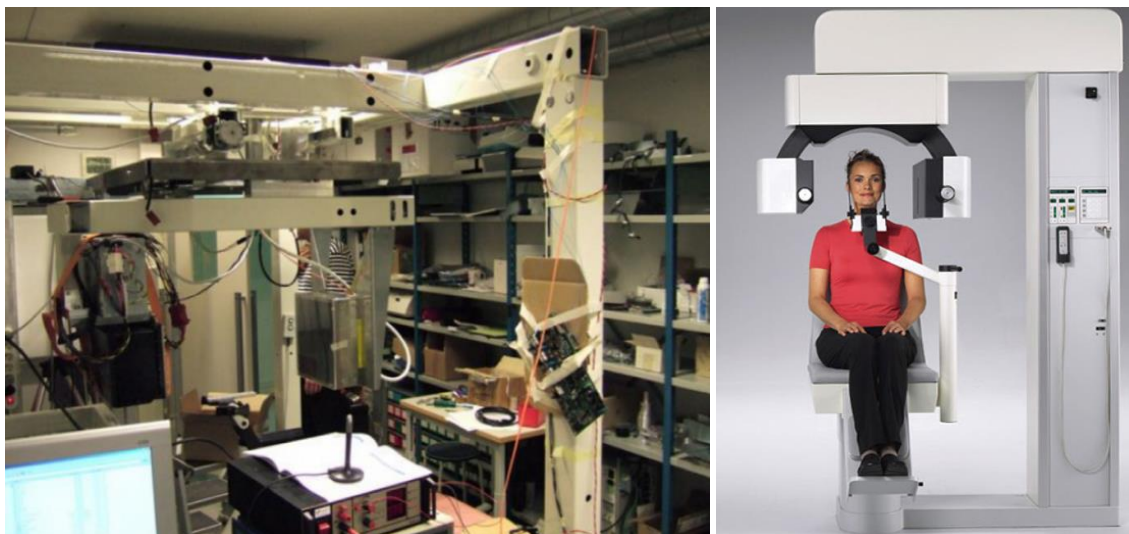


Fig. 66 Left: Early prototype of a tomographic unit with six degrees of motion by Prof. Tammissalo. Right: the SCANORA dental (spiral) tomographic unit (Soredex, Tuusula, Finland), released in 1988. Different programs were available; the selection of the program selection was performed on a panoramic image. Courtesy of Soredex Oy and J. Mudrak.

XI. CONE-BEAM COMPUTED TOMOGRAPHY

The development of dedicated dental CBCT units was a logical outcome of the increased necessity for cross-sectional imaging in dentistry, primarily due to the increasing popularity of implant placement. Whereas helical CT has been applied in dentistry since its inception, and is still used to some extent, CBCT has become the convention in 3D dental imaging. In the footsteps of dental tomography (section X), dental CBCT scanners were developed in the 1990s. Prior to dental CBCT, this technology was used for applications such as angiography as early as 1982 [128]. Commercialization of dental CBCT happened in parallel in Europe [129] and Japan [130], followed by the USA. The number of dental CBCT models on the market has increased from 23 devices in 2008 [131], to 43 devices in 2013 [132], to 280 devices at the time of writing [133].

The technical aspects of CBCT have been described in a previous review [134], and patient dose has been measured by a multitude of studies [135-140]. Most CBCT models have the patient in a standing or seated position; a few units use supine patient positioning (Fig. 67). The first generation(s) dental CBCT units used image intensifier detector systems, but from the mid-2000s the use of scintillator-type (indirect) flat panel detectors (FPD) increased and has since become the norm. FPDs showed several benefits over image intensifier systems, including reduced bulk, improved spatial resolution at equal noise level, and higher geometric accuracy [141]. Several of the first- and second-generation CBCT units used continuous exposure, with an exposure time typically between 15-20 s. Due to the limited frame rate of FPD detectors and the presence of afterglow, pulsed X-ray exposure was introduced, with total exposure time decreasing to a few seconds. Automatic exposure control (AEC) is still largely absent in dental CBCT: a pre-scan AEC system based on the signal distribution of a scout image (topogram) was introduced on NewTom (QR, Italy) systems several years ago (SafeBeam™); more recently, the same manufacturer has introduced tube current modulation during the scan based on pre-set mA curves [142], with a relatively lower tube output for lateral projection angles due to the lower attenuation. The majority of current commercial CBCT units, however, involve manual exposure set-up and/or the use of presets (*e.g.* adult male/female vs child protocols). Reconstruction is typically based on the adapted filtered backprojection technique by Feldkamp-Davis-Kress [143].



Fig. 67 Seated (left), standing (middle) and supine (right) cone-beam computed tomography units.

Following the implementation of dual-energy scanning in medical CT, dual-energy CBCT was recently introduced [144,145]. The main potential benefit of dual-energy CBCT in dentistry is artefact reduction; dual-energy imaging could also allow for improved soft tissue contrast and/or density estimation, but there are few clinical indications in dentistry for which this could be of benefit. Metal artefacts, however, are one of the most prominent artefacts in dental CBCT, often deteriorating image quality to unacceptable levels. Whereas several CBCT units have incorporated a metal artefact reduction (MAR) technique in their reconstruction algorithm, several studies have shown that diagnostic image quality was not improved [146,147] or even impaired [148] when using MAR. This is likely due to the fact that currently used MAR techniques on commercial units are fast, interpolation-based techniques; while they may lead to an esthetically improved image, the additional diagnostic information provided by MAR can be limited. Iterative techniques that model the physics of the system could offer a more robust solution to metal artefacts, but they are often computationally expensive and thus impractical in a dental clinical environment. The use of artificial intelligence for real-time artefact correction could combine the robustness of physics-based correction with the speed of backprojection, but requires further validation [149,150].

Another common artefact is due to patient motion; while this is mainly apparent in cases with severe movement, even swallowing, breathing or reverberation of the jaw causes some degree of blurring. Motion correction based on selective elimination of projections was introduced ca. 2007 (Iluma, IMTEC Imaging, USA) and has been implemented on a few CBCT models; it has been shown that this approach can reduce motion artefacts and thus avoid the need for re-exposure

[151]. Recently, head tracking (X1, 3Shape, Denmark) [152] and reconstruction-based motion correction (CALM™, Planmeca, Helsinki, Finland) [153] were introduced.

XII. RADIOLOGICAL VIEWING/DISPLAY SYSTEMS

Along with the drastic improvement in image quality in the early years in radiographs came the necessity of appropriate viewing systems (Fig. 68-72). Once film became ubiquitous in radiography, so did the lightbox [154]. Furthermore, projections were used for the purpose of zooming, and specialized equipment was designed for stereoscopic ('parallax') radiology as mentioned in section V.



Fig. 68 Left: Vintage lightbox (ca. 1930s). Picture formerly hosted on Hoarde Vintage; original source unknown. Right: dental X-ray projector (ca. 1940, Spencer Lens Company). Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [155].



Fig. 69 X-ray film illuminator; estimated manufacturing date 1950s. The level of illumination by the incandescent bulb was adjustable. Figure and information provided by the Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection under a non-transferable, non-exclusive, limited license [156].



Fig. 70 High intensity illuminator (Picker X-Ray, USA) with attached magnifying glass. Courtesy of S. Anamali (University of Iowa)



Fig. 71 Vintage intra-oral film mount. Courtesy of A. Wenzel (Aarhus University)



Fig. 72 Left: Radiograph copying machine. Courtesy of A. Al-Ekrish (King Saud University) Right: intra-oral film duplicator. Courtesy of S. Anamali (University of Iowa).

For digital radiographs, although it still occurs to this day that they are printed on film (*e.g.* for external requests), cathode ray tube (CRT) screens were initially used. More recently, (1) liquid-crystal display (LCD) with thin-film transistor (TFT) technology and (2) light-emitting-diode (LED) display systems have become the norm. With recent improvements in commercial off-the-shelf monitor technology, the benefit of costly ‘medical grade’ displays has been questioned, as the improved technical specifications of the latter type could be overcome by proper use of software tools like display calibration, window/level adjustment, zooming and filters. Furthermore, several recent studies have investigated the use of tablets for displaying dental radiographs. For the diagnosis of vertical root fractures on periapical radiographs, no difference was found between PC displays and tablets [157]. In the evaluation of caries on bitewing radiographs, increased performance was found for DICOM-calibrated consumer-grade displays vs. uncalibrated displays [158], although diagnostic accuracy was not assessed due to the absence of a ground truth. Tablet displays showed an almost equal performance to calibrated consumer-grade displays, both of which performed slightly worse than medical-grade displays [158]. Another study found that tablet displays performed equal to PACS-LCD monitors in the identification of anatomical landmarks in panoramic and lateral cephalometric radiographs [159]. In an evaluation of anatomical structures on cone-beam CT scans, a tablet display, PACS-LCD monitor, consumer-grade LCD monitor and laptop display all showed similar performance [160].

Recently, the use of augmented reality and virtual reality in image-guided surgery, both during pre-operative planning and intra-operatively, has gained attention [161-163]; further validation of this technology is needed in terms of effects on surgical time and outcome.

A NOTE ON HISTORICAL ACCURACY, COMPLETENESS AND SCOPE

During the preparation of this review, care was taken to ensure accuracy in terms of people, actions, dates and technology, relying on primary sources when possible. However, due to the limited availability/accessibility of such sources (most famously Röntgen’s notes, burned at his own request after his death), and conflicting information found in secondary/tertiary sources, a fully accurate representation of the 125-year old history of dental radiography cannot be guaranteed. The discrepancy between previously published information was mainly apparent when dealing with issues such as “In [year], [person/company] was the first to [develop/use something] in [country/region].”

Furthermore, several role-players in dental X-ray history were omitted from this review, either due to a lack of information regarding their exact contribution, or for conciseness. Little or no history of CT was included, as this is better suited for a separate review. Modalities that do not make use of ionizing radiation (*i.e.* magnetic resonance imaging, ultrasound) are outside of the scope of this review.

ACKNOWLEDGMENTS

R. Pauwels is supported by the European Union Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement number 754513 and by Aarhus University Research Foundation (AIAS-COFUND).

The author is heavily indebted to the extensive collection of historical information on dental radiography performed by authors of previously published work, and would like to emphasize in particular the publications by AAOMR [29], Campbell

[70], Forrai [11], Glenner [52], Hallikainen [100], Jacobsohn & Fedran [16], Martinez [17], and Serman & Singer [19], and to recommend each of them for further reading.

A special thanks to Asma'a Al-Ekrish (King Saud University), Sindhura Anamali (University of Iowa), Johan K.M. Aps (University of Western Australia), Daniel Bednarek (University at Buffalo, Museum of Radiology and Medical Physics), Pam Bonee & Paul Frame (Oak Ridge Associated Universities, Health Physics Historical Instrumentation Museum Collection), Keith Horner (University of Manchester), Instrumentarium (Tuusula, Finland), Freny Karjodkar (Nair Hospital Dental College), Jörg Mudrak, J Morita (Kyoto, Japan), Pisha Pittayapat (Chulalongkorn University), Kaustubh Sansare (Nair Hospital Dental College), Steven R. Singer (Rutgers, The State University of New Jersey), Phonkit Sinpitaksakul (Chulalongkorn University), Soredex (Tuusula, Finland), Slavik Tabakov (King's College London), Karla de Faria Vasconcelos (Catholic University of Leuven), Rick Waters, Ann Wenzel (Aarhus University) and Stuart White (University of California, Los Angeles) for providing various source material.

The Author declares that there is no conflict of interest.

REFERENCES

- Röntgen W (1895) Ueber eine neue Art von Strahlen. Vorläufige Mitteilung. Aus den Sitzungsberichten der Würzburger Physik.-medic. Gesellschaft Würzburg: 137-147
- Behling R (2018) X-ray tubes development - IOMP history of medical physics. *Med Phys Int*: 6:8-55
- Walden TL Jr (1991) The first radiation accident in America: a centennial account of the x-ray photograph made in 1890. *Radiology* 181:635-639
- Conrad C (2011) Vergleich der metrischen Genauigkeit von extraoralen Röntgenverfahren: in vitro Studie an humanen Schädelpräparaten. Dissertation, Justus Liebig University Giessen.
- Gianfaldoni S, Gianfaldoni R, Wollina U et al. (2017) An Overview on Radiotherapy: From Its History to Its Current Applications in Dermatology. *Open Access Maced J Med Sci* 5:521-525 DOI 10.3889/oamjms.2017.122
- Sansare K, Khanna V, Karjodkar F (2011) Early victims of X-rays: a tribute and current perception. *Dentomaxillofac Radiol* 40:123-125 DOI 10.1259/dmfr/73488299
- Harrison F (1896) The New Photography and its Application to Dental Practice. *J Br Dent Assoc* 17:343-344
- Figures K, Smith C (2012) A profile of Frank Harrison: a pioneering Sheffield dentist from 100 years ago. *Br Dent J* 213:405-408 DOI 10.1038/sj.bdj.2012.931
- Zesch S, Panzer S, Rosendahl W, et al (2016) From first to latest imaging technology: Revisiting the first mummy investigated with X-ray in 1896 by using dual-source computed tomography. *Eur J Radiol Open* 25:172-181. DOI 10.1016/j.ejro.2016.07.002
- König W (1896) 14 Photographien mit Röntgen-Strahlen aufgenommen im Physikalischen Verein zu Frankfurt a. M. Johann Ambrosius Barth, Leipzig.
- Forrai J (2007) History of X-ray in dentistry. *Rev Clin Pesq Odontol* 3:205-211
- Langland OE, Peter Fortier A (172) C. Edmund Kells. *Oral Surg Oral Med Oral Path* 34:680-689 DOI 10.1016/0030-4220(72)90353-2
- Kells CE (1926) Three score years and nine. Self-published.
- Price WA (1904) The technique necessary for making good dental skiagraphs. *Dent Items Interest* 26:161-171
- McCormack FW (1920) A Plea for a Standardized Technique for Oral Radiography, with an Illustrated Classification of Findings and Their Verified Interpretations. *J Dent Res* 2:467-509 DOI 10.1177/00220345200020030401
- Jacobsohn PH, Fedran RJ (1995) Making Darkness Visible: The Discovery of X-ray and Its Introduction to Dentistry. *J Am Dent Assoc* 126:1359-1366
- Martinez B (2013) In a New Light: Early X-Ray Technology in Dentistry, 1890-1955. Dissertation, Arizona State University.
- Morton WJ (1896) The x-ray and its application in dentistry. *Dent Cosmos* 38:478-485
- Serman N, Singer SR (1995) The history of dental radiology. *N Y State Dent J* 61:78-81
- Morton WJ, Hammer EW (1896) The X-Ray or Photography of the Invisible and its Value in Surgery. American Technical Book Co., New York.
- Price WA (1900) The Roentgen rays with associated phenomena and their applications to dentistry. *Dent Cosmos* 42:117-129
- Kells CE (1926) Thirty years' experience in the field of radiography. *J Am Dent Assoc* 13:693-711
- Kells CE (1927) Roentgen-ray burns. *J Am Dent Assoc* 14:235
- Rollins WH (1901) X-light kills. *Boston Med Surg J* 144:173
- Rollins WH (1903) Notes on x-light: the effect of x-light on the crystalline lens. *Boston Med Surg J* 148:364-365.
- Wynbrandt J (1998) The Excruciating History of Dentistry. St. Martin's Griffin, New York
- Kathren RL (1964) William Rollins (1852-1929): X-ray protection pioneer. *J Hist Med Allied Sci* 19:287-294
- Roeder F, von Rechenberg I, d'Hoedt B, et al. (2011). Spatial relation between a rigid (digital) intraoral X-ray receptor and longitudinal axes of maxillary teeth. *Clin Oral Investig* 15:715-9. DOI 10.1007/s00784-010-0430-x
- AAOMR at https://www.aaomr.org/assets/History/early_pioneers_of_oral_and_m.pdf
- Richards AG (1966) New concepts in dental X-ray machines. *J Am Dent Assoc* 73:69-76 DOI 10.14219/jada.archive.1966.0232
- 'Oradlist' Oral Radiology Discussion Group contribution by R. Molteni (2013)
- Rushton VE, Horner K (1994) The acceptability of five periapical radiographic techniques to dentists and patients. *Br Dent J* 177:325-331
- Peciuliene V, Rimkuvienė J, Maneliene R, et al (2009) Use of dental radiography among Lithuanian general dentists. *Stomatologija* 11:77-82
- Hedley WS (1898) Radiostereoscopy. *Lancet* 151:639
- Clark CA (1910) A Method of ascertaining the Relative Position of Unerupted Teeth by means of Film Radiographs. *Proc R Soc Med* 3:87-90
- Armstrong C, Johnston C, Burden D, et al (2003) Localizing ectopic maxillary canines--horizontal or vertical parallax?. *Eur J Orthod* 25:585-589
- Hubar JS, Caballero P (2017) Localization of Objects (SLOB Rule). In: *Fundamentals of Oral and Maxillofacial Radiology*. John Wiley & Sons, Hoboken DOI 10.1002/9781119411871.ch18
- Richards AG (1952) Roentgenographic localization of the mandibular canal. *J Oral Surg* 10:325-329
- Richards AG (1953) The buccal object rule. *J Tennessee State Dent Assoc* 33:263-268
- Ingle JI, Bakland LK, Baumgartner JC (2008). *Ingle's Endodontics* 6 (6th ed.). BC Decker, Hamilton
- Pieper AF, Kester GL (1931) Stereoscopic view box. U.S. Pat. No. 1808176.

42. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/Stereo%20viewer.htm>
43. Pfahler GE (1908) The use of the roentgen rays in dentistry. *Dent Cosmos* 50:916-919
44. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/dentoscope.htm>
45. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/indianheadreflector.htm>
46. Rollins WH (1898) Roentgen-ray notes. *Electr Rev* 32:12
47. Kells CE (1899) Roentgen rays. *Dent Cosmos* 41:1014-1029
48. Borden WC (1898) The use of the Röntgen ray by the medical department of the United States military in the war with Spain.
49. Mackee GM, Remer J (1914) Measurement of the amount of x ray employed in making dental radiographs. *Dent Cosmos* 56:35-42
50. Jacobsohn PH, Fedran RJ (1995) Harnessing the x-ray: Coolidge's contribution. *J Am Dent Assoc* 126:1365 DOI 10.14219/jada.archive.1995.0045
51. Coolidge WD (1919). X-ray apparatus. U.S. Patent 1408989
52. Glenner RA (1975) 80 years of dental radiography. *J Am Dent Assoc* 90:549-563.
53. Science Museum Group at <https://collection.sciencemuseumgroup.org.uk/objects/co100154/cdx-model-e-dental-x-ray-unit-chicago-usa-1935-1936-x-ray-machine>
54. Coolidge WD (1919) X-ray Apparatus. U.S. Patent 1310061.
55. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/xraytubescoolidge/Victordental.htm>
56. UB Museum of Radiology and Medical Physics at <http://ubradiologymuseum.com/>
57. Gross MJ (1935) Progress in the Design of Shock Proof Roentgen Tubes for Therapy and Industrial Roentgenography. *Am J Roent Radium Therapy* 34:518-522
58. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/xraytubescoolidge/GEXPD.htm>
59. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/xraytubescoolidge/grossshockproof.htm>
60. Science Museum Group at <https://collection.sciencemuseumgroup.org.uk/objects/co100221/artiflex-dental-unit-by-siemens-reiniger-werke-a-dental-units>
61. Velders XL, van Aken J, van der Stelt PF (1991) Absorbed dose to organs in the head and neck from bitewing radiography. *Dentomaxillofac Radiol* 20:161-165
62. Shetty A, Almeida FT, Ganatra S, et al. (2019) Evidence on radiation dose reduction using rectangular collimation: a systematic review. *Int Dent J* 69:84-97. DOI 10.1111/idj.12411
63. Magill D, Ngo NJH, Felice MA, et al. (2019) Kerma area product (KAP) and scatter measurements for intraoral X-ray machines using three different types of round collimation compared with rectangular beam limiter. *Dentomaxillofac Radiol* 48:20180183. DOI 10.1259/dmfr.20180183.
64. Ludlow JB, Davies-Ludlow LE, White SC (2008) Patient risk related to common dental radiographic examinations: the impact of 2007 International Commission on Radiological Protection recommendations regarding dose calculation. *J Am Dent Assoc* 139:1237-1243.
65. Pittayapat P, Jacobs R, De Valck E, et al. (2012) Forensic odontology in the disaster victim identification process. *J Forensic Odontostomatol* 30:1-12
66. Berkhout WER, Suomalainen A, Brullmann D, et al. (2015) Justification and good practice in using handheld portable dental x-ray equipment: a position paper prepared by the European Academy of Dentomaxillofacial Radiology (EADMFR) *Dentomaxillofac Radiol* 44:20140343 DOI 10.1259/dmfr.20140343
67. HERCA (2014) Position statement on use of handheld portable dental x-ray equipment. <http://www.herca.org/uploaditems/documents/HERCA%20position%20statement%20on%20use%20of%20handheld%20portable%20dental%20x-ray%20equipment.pdf>
68. Thunthy KH. Timeline of Oral and Maxillofacial Radiology. https://www.aomr.org/assets/History/timeline_of_omr.pdf
69. Röntgen W (1897) Further Observations on the Properties of X-ray. Prussian Academy of Sciences, Berlin.
70. Campbell DJ (1995) A brief history of dental radiography. *N Z Dent J* 91:127-133
71. U.S. Food and drug administration. Nationwide Evaluation of X-Ray Trends (NEXT). *Dental Radiography: Doses and Film Speed*.
72. Bolin L (1925) Dental x-ray-film package. U.S. Pat. No. 1,537,925
73. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/Dental%20Film.htm>
74. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/Dental%20cassettes.htm>
75. Geo. W. Brady & Company (1937) Paragon X-ray Supplies and Accessories.
76. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/intra-oral%20film%20blocks.htm>
77. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/intra-oral%20film%20blocks.htm>
78. Kells CE (1922) Practical development of dental films. *Dent Items Interest* 44:927-937
79. Yoshida M, Yoshihara H, Honda E (2018) History of Digital Detectors in Intraoral Radiography. *Dent Health Curr Res* 4 DOI 10.4172/2470-0886.1000135
80. Duret F, Coste BC, Duret, B (1988) The Radio Visiography (RVG): where reality surpasses radiological fiction a hope that is becoming reality. *J Dent Pract Admin* 5:138-140
81. Borg E (1999) Some characteristics of solid-state and photo-stimulable phosphor detectors for intra-oral radiography. *Swed Dent J Suppl* 139:1-67
82. Borg E, Grondahl HG (1996) On the dynamic range of different X-ray photon detectors in intra-oral radiography. a comparison of image quality in film, charge-coupled device and storage phosphor systems. *Dentomaxillofac Radiol* 25: 82-88.
83. Attalmanan AG, Borg E, Gröndahl HG (2001) Signal-to-noise ratios of 6 intraoral digital sensors. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 91:611-615
84. Wenzel A, Møystad A (2001) Experience of Norwegian general dental practitioners with solid state and storage phosphor detectors. *Dentomaxillofac Radiol* 30:203-208
85. ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP* 37:1-332
86. Ludlow JB, Davies-Ludlow LE, White SC (2008) Patient risk related to common dental radiographic examinations: the impact of 2007 International Commission on Radiological Protection recommendations regarding dose calculation. *J Am Dent Assoc* 139:1237-1243
87. Pogorzelska-Stronczak B (1963) Attempted application of xeroradiography in stomatology. *Pol Przegl Radiol Med Nukl* 27:265-275

88. Ferguson MM, Davison M, Evans A, et al. (1976) Application of xeroradiography in sialography. *Int J Oral Surg* 5:176-179
89. Gratt BM, Sickles EA, Nguyen NT (1979) Dental xeroradiography for endodontics: a rapid X-ray system that produces highquality images. *J Endod* 5:266-270
90. Jeromin LS, Geddes GF, White SC, et al. (1980) Xeroradiography for intraoral dental radiology. A process description. *Oral Surg Oral Med Oral Pathol* 49:178-183
91. Barkhordar RA, Nicholson RJ, Nguyen NT, et al. (1987) An evaluation of xeroradiographs and radiographs in length determination in endodontics. *Oral Surg Oral Med Oral Pathol* 64:747-750
92. Gratt BM, Sickles EA, Nguyen NT (1979) Dental xeroradiography for endodontics: a rapid X-ray system that produces highquality images. *J Endod* 5:266-270
93. Wilson NH, Grant AA (1986) A clinical trial of dental xeroradiography. *Br Dent J* 161:327-335
94. Udoye CI, Jafarzadeh H (2010) Xeroradiography: stagnated after a promising beginning? A historical review. *Eur J Dent* 4:95-99
95. Tammissalo EH (1975) Professor Yrjö v. Paatero - the pioneer of panoramic oral tomography. *Dentomaxillofac Radiol* 4:53-56. DOI 10.1259/dmfr.1975.0010
96. Zulauf AF (1922) Panoramic X-ray apparatus. U.S. Patent No 1408559
97. Numata H (1933) Consideration of the parabolic radiography of the dental arch. *J Shimazu Stud* 10:13
98. Heckmann K (1939) Die Röntgenperspektive und ihre Umwandlung durch eine neue Aufnahmetechnik. *RöFo* 60:144-157
99. Dickson G, Hudson DC, Kumpula JW (1957) A panoramic x-ray dental machine. *U S Armed Forces Med J* 13:46-55
100. Hallikainen D (1996) History of panoramic radiography. *Acta Radiol* 37:441-445
101. Paatero YV (1952) Thickness of layer reproduced on pantomogram in relation to location of the object, speed of rotation, and divergence of roentgen rays. *Soumen Hammaslääkäriseuran Toimituksia* 48:113-128
102. Paatero YV (1953) Radiography of the temporo-mandibular joint. A new method. *Ann Chir Gynaecol Fenn* 42:259-264
103. Paatero YV (1954) Geometrical study on possibilities of making double eccentric pantomograms with a single exposure. *Suomen Hammaslääkäriseuran Toimituksia* 50:36-43
104. Paatero YV (1955) Die Anwendungen der Pantomographie für klinische Untersuchungen. *RöFo* 82:525-528
105. Paatero YV (1957) Pantomography of spherical layers. *Acta Radiol* 48:181-187
106. Blackman S (1956) Mass dental radiography. *Radiography* 22:21-25
107. *Br J Radiol.* 1979 Sep;52(621):727-34. Doses to patients from pantomographic and conventional dental radiography. Wall BF, Fisher ES, Paynter R, Hudson A, Bird PD.
108. McDavid WD, Tronje G, Welander U (1989) Image layers in the Zonarc. *Dentomaxillofac Radiol* 18:1-10
109. Kashima I, Kanno M, Higashi T, et al. (1985) Computed panoramic tomography with scanning laser-stimulated luminescence. *Oral Surg Oral Med Oral Pathol* 60:448-453
110. McDavid WD, Dove SB, Welander U, et al. (1991) Electronic system for digital acquisition of rotational panoramic radiographs. *Oral Surg Oral Med Oral Pathol* 71:499-502
111. Dove SB, McDavid WD, Welander U, et al. (1992) Preliminary evaluation of a digital system for rotational panoramic radiography. *Oral Surg Oral Med Oral Pathol* 73:623-632
112. Qiang W, Qiang F, Lin L (2019) Estimation of effective dose of dental x-ray devices. *Radiat Prot Dosimetry.* 183:417-421. DOI 10.1093/rpd/ncy159
113. Benchimol D, Koivisto J, Kadesjö N, et al. (2018) Effective dose reduction using collimation function in digital panoramic radiography and possible clinical implications in dentistry. *Dentomaxillofac Radiol* 47:20180007. DOI 10.1259/dmfr.20180007
114. Gijbels F, Jacobs R, Bogaerts R, et al. (2005) Dosimetry of digital panoramic imaging. Part I: Patient exposure. *Dentomaxillofac Radiol* 34:145-149
115. IAEA at <https://www.iaea.org/resources/rpop/resources/training-material#11>
116. Broadbent HB (1931) A new X-ray technique and its application to orthodontia. *Angle Orthod* 1:45-66
117. Hofrath H (1931) Die Bedeutung der Röntgenfern- und Abstandsaufnahme für die Diagnostik der Kieferanomalien. *Fortschritte Orthod* 1:232-258
118. Broadbent HB (1937) The face of the normal child. *Angle Orthod* 7:183-208.
119. Ricketts RM (1969) The evolution of diagnosis to computerized cephalometrics. *Am J Orthod Dentofacial Orthop* 55:795-803
120. Barsony T (1925) Idiopathic Dilatation of Stenson's Duct. *Klin Wchnschr* 4:2500-2501
121. Holt JF (1957). Sialography. *Radiology* 68:584-585
122. Rubin P, Blatt M (1955) Sialography, Preliminary Report. *Univ Michigan M Bull* 21:57-63
123. Rubin P, Blatt M, Holt JF, Maxwell JH (1955) Physiological or Secretory Sialography. *Ann Oto Rhin Laryng* 64:667-688
124. Afzelius P, Nielsen MY, Ewertson C, et al. (2016) Imaging of the major salivary glands. *Clin Physiol Funct Imaging* 36:1-10. DOI 10.1111/cpf.12199
125. Littleton JT, Littleton MLD (1996) Conventional tomography. A History of the Radiological Sciences. American Roentgen Society, Leesburg.
126. Tammissalo E, Hallikainen D, Kanerva H, et al. (1992) Comprehensive oral X-ray diagnosis: Scanora multimodal radiography. A preliminary description. *Dentomaxillofac Radiol* 21:9-15
127. Science Museum Group at <https://collection.sciencemuseumgroup.org.uk/objects/co440061/tomograph-united-kingdom-1950-1959-tomograph>
128. Robb RA (1982) The dynamic spatial reconstructor: an x-ray video-fluoroscopic CT scanner for dynamic volume imaging of moving organs. *IEEE Trans Med Imaging* 1:22-33
129. Mozzo P, Procacci C, Tacconi A, et al. (1998) A new volumetric CT machine for dental imaging based on the cone-beam technique: preliminary results. *Eur Radiol* 8:1558-1564
130. Arai Y, Tammissalo E, Iwai K, et al. (1999) Development of a compact computed tomographic apparatus for dental use. *Dentomaxillofac. Radiol* 28:245-248
131. Kau CH, Bozic M, English J, et al. (2009) Cone-beam computed tomography of the maxillofacial region: an update. *Int J Med Robot Comput Assist Surg* 5:366-80
132. Nemtoi A, Czink C, Haba D, et al. Cone beam CT: a current overview of devices. *Dentomaxillofacial Radiol* 42:20120443
133. Gaëta-Araujo H, Alzoubia T, Vasconcelos KF, et al. Cone-beam computed tomography in Dentomaxillofacial radiology: a two-decade overview. Pre-published.
134. Pauwels R, Araki K, Siewerdsen JH, et al. (2015) Technical aspects of dental CBCT: state of the art. *Dentomaxillofac Radiol* 44:20140224 DOI 10.1259/dmfr.20140224
135. Al-Okshi A, Lindh C, Salé H, et al. (2015) Effective dose of cone beam CT (CBCT) of the facial skeleton: a systematic review. *Br J Radiol* 88:20140658 DOI 10.1259/bjr.20140658
136. Ludlow JB, Timothy R, Walker C, et al. (2015) Effective dose of dental CBCT-a meta analysis of published data and additional data for nine CBCT units. *Dentomaxillofac Radiol* 44:20140197 DOI 10.1259/dmfr.20140197
137. Pauwels R, Beinsberger J, Collaert B, et al. (2012) Effective dose range for dental cone beam computed tomography scanners. *Eur J Radiol* 81:267-271 DOI 10.1016/j.ejrad.2010.11.028

138. Bornstein MM, Scarfe WC, Vaughn VM, et al. (2014) Cone beam computed tomography in implant dentistry: a systematic review focusing on guidelines, indications, and radiation dose risks. *Int J Oral Maxillofac Implants* 29S:55-77 DOI 10.11607/jomi.2014suppl.g1.4
139. Rottke D, Patzelt S, Poxleitner P, et al. (2013) Effective dose span of ten different cone beam CT devices. *Dentomaxillofac Radiol* 42:20120417 DOI 10.1259/dmfr.20120417
140. Pauwels R (2015) Cone beam CT for dental and maxillofacial imaging: dose matters. *Radiat Prot Dosimetry* 165:156-161. DOI 10.1093/rpd/ncv057
141. Baba R, Konno Y, Ueda K et al. (2002) Comparison of flat-panel detector and image-intensifier detector for cone-beam CT. *Comput Med Imaging Graph* 26:153-158
142. Stratis A, Zhang G, Lopez-Rendon X, et al. (2017) Two examples of indication specific radiation dose calculations in dental CBCT and Multidetector CT scanners. *Phys Med* 41:71-77 DOI 10.1016/j.ejmp.2017.03.027
143. Feldkamp LA, Davis LC, Kress JW (1984) Practical cone-beam algorithm. *J Opt Soc Am A* 1:612-619
144. Kim HJ, Kim JE, Choo J, et al. (2019) A clinical pilot study of jawbone mineral density measured by the newly developed dual-energy cone-beam computed tomography method compared to calibrated multislice computed tomography. *Imaging Sci Dent* 49:295-299 DOI 10.5624/isd.2019.49.4.295
145. Zhu L, Chen Y, Yang J, et al. (2019) Evaluation of the dental spectral cone beam CT for metal artefact reduction. *Dentomaxillofac Radiol* 48:20180044 DOI 10.1259/dmfr.20180044
146. Kamburoğlu K, Yılmaz F, Yeta EN, et al. (2016) Assessment of furcal perforations in the vicinity of different root canal sealers using a cone beam computed tomography system with and without the application of artifact reduction mode: an ex vivo investigation on extracted human teeth. *Oral Surg Oral Med Oral Pathol Oral Radiol* 121:657-665 DOI 10.1016/j.oooo.2016.01.010
147. de-Azevedo-Vaz SL, Peyneau PD, Ramirez-Sotelo LR, et al. (2016) Efficacy of a cone beam computed tomography metal artifact reduction algorithm for the detection of peri-implant fenestrations and dehiscences. *Oral Surg Oral Med Oral Pathol Oral Radiol* 121:550-556 DOI 10.1016/j.oooo.2016.01.013
148. Bezerra IS, Neves FS, Vasconcelos TV, et al. (2015) Influence of the artefact reduction algorithm of Picasso Trio CBCT system on the diagnosis of vertical root fractures in teeth with metal posts. *Dentomaxillofac Radiol* 44:20140428 DOI 10.1259/dmfr.20140428
149. Pauwels R, Oliveira-Santos C, Oliveira ML, et al. (2019) Artefact reduction in cone beam CT through deep learning: a pilot study using neural networks in the projection domain. The 22nd International Congress of DentoMaxilloFacial Radiology, Philadelphia, PA, USA, 2019
150. Pauwels R, Oliveira-Santos C, Watanabe P, et al. (2020) Correction of exomass artefacts in dental cone-beam CT using convolutional neural networks poster. EPOS C-14953, European Congress of Radiology, Vienna, Austria, 2020
151. Yeung AWK, Azevedo B, Scarfe WC, et al. (2019) Patient motion image artifacts can be minimized and re-exposure avoided by selective removal of a sequence of basis images from cone beam computed tomography data sets: a case series. *Oral Surg Oral Med Oral Pathol Oral Radiol*. In press. DOI 10.1016/j.oooo.2019.07.003
152. 3Shape at <https://www.3shape.com/en/scanners/x1-cbct>
153. Planmeca at <https://www.planmeca.com/imaging/3d-imaging/planmeca-calm/>
154. Seeley GW, McNeill K, Dallas WJ (1987) Displays in radiology: past, present, and future. *Radiographics* 7:1261-1266
155. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/Dental%20xray%20projector.htm>
156. Oak Ridge Associated Universities (ORAU) Health Physics Historical Instrumentation Museum Collection at <https://www.ornl.gov/ptp/collection/Radiology/xrayviewer.htm>
157. Vasconcelos TV, Santaella GM, Nascimento HA, et al. (2016) Digital radiographs displayed on different devices: effect on the detection of vertical root fractures. *Int Endod J* 49:386-392 DOI 10.1111/iej.12466
158. Kallio-Pulkkinen S, Huuonen S, Haapea M, et al. (2016) Effect of display type, DICOM calibration and room illuminance in bitewing radiographs. *Dentomaxillofac Radiol* 45:20150129 DOI 10.1259/dmfr.20150129
159. Tadinada A, Mahdian M, Sheth S, et al. (2015) The reliability of tablet computers in depicting maxillofacial radiographic landmarks. *Imaging Sci Dent* 45:175-180. DOI 10.5624/isd.2015.45.3.175
160. Carrasco A, Jalali E, Dhingra A, et al. (2017) Analyzing dental implant sites from cone beam computed tomography scans on a tablet computer: a comparative study between iPad and 3 display systems. *Implant Dent* 26:393-399 DOI 10.1097/ID.0000000000000595
161. Kwon HB, Park YS, Han JS (2018) Augmented reality in dentistry: a current perspective. *Acta Odontol Scand* 76:497-503 DOI 10.1080/00016357.2018.1441437
162. Bartella AK, Kamal M, Scholl I, et al. (2019) Virtual reality in preoperative imaging in maxillofacial surgery: implementation of "the next level"? *Br J Oral Maxillofac Surg* 57:644-648 DOI 10.1016/j.bjoms.2019.02.014
163. Jiang W, Ma L, Zhang B, et al. (2018) Evaluation of the 3D augmented reality-guided intraoperative positioning of dental implants in edentulous mandibular models. *Int J Oral Maxillofac Implants* 33:1219-1228 DOI 10.11607/jomi.6638

Contacts of the corresponding author:

Author: Ruben Pauwels
 Institute: Aarhus Institute of Advanced Studies
 Street: Høegh-Guldbergs Gade 6B
 City: 8000 Aarhus
 Country: Denmark
 Email: pauwelsruben@hotmail.com

