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DEGLI STUDI DI TRIESTE



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for Theoretical Physics

Issue #



# Abstracts Booklet of the MMP Thesis (3rd cycle)

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Title:

## Commissioning of a mHDR Brachytherapy System and Implementation of Transit Dose calculation.

**Prospective/Objective:** To commissioning a new Flexitron treatment delivery Brachytherapy system, implement the Transit dose calculations and validate the Advanced Collapsed cone Engine (ACE) dose calculation engine of Oncentra Brachy (OcB) treatment planning system using an  $^{192}\text{Ir}$  source.

The Acceptance test are mandatory as part of the commissioning of a new machine as recommended by the AAPM TG-43 and TG-186. The next challenge was to introduce transit dose calculation for to be confident if transit dose is significant in plans performed in female patients that are subjected to intracavitary technique. Accurate dose calculation is a crucial part of the treatment planning in Brachytherapy. Several reviews have put the attention on TPS with model-based algorithms that better take into account the effects of the patient individual distribution of tissues and applicator shielding attenuation, aspects that are not taken in account by TG-43 formalism which simply maps homogeneous water dose distributions onto the patient.

**Materials and methods.** Following the guidelines (AAPM TG-43, TG-56, TG-59, TG-41, TG-186 and ESTRO booklet 8) commissioning was performed for Flexitron Brachytherapy system and

Oncentra brachy TPS V4.5. Wall ionization chamber, portables dosimeters, virtual water phantom, set of applicators (for calibration and treatment) were used during commissioning. The new test was implemented for the measures of tip applicator distance. Transit dose was calculated, thanks to the software developed in MatLab that permits to calculate dynamic doses in a faster way, and measured with calibrated Gafchromic films. Transit dose was evaluated also for another brachytherapy machine, Nucletron Microselectron. As for the commissioning of the ACE algorithm, we adapted the process recommended by TG-186.

**Results.** The periodic tests of radioprotection and emergency procedure were performed successfully and in good agreement with the manufacturer; measurements of ambient dosimetry are in agreement with Italian radioprotection law. Source positioning is within  $\pm 0.5\text{mm}$  from the expected position. The maximum efficiency collecting point of wall ionization chamber was found at 1135 mm and the measure of air kerma strength within 0.4% respect to the value of source certificate. The linearity of the timer is reproducible and error is less than  $\pm 0.01\%$ . Tip applicator distance was evaluated respect to declared values for vaginal and fletcher applicators with

Gafchromic films (agreement better than 4.2%) and with Oncentra TPS (perfect agreement for Fletcher applicator and with a difference of 7.1% for vaginal one). For transit dose, Gafchromic films were calibrated between 20cGy and 180cGy. Considering a source of 10Ci activity (that is a typical value of new sources), the transit dose in contact with the applicator for single fraction calculated with MatLab for Flexitron is 7.2cGy, with an agreement of 4% with the measured one. Applying the same conditions, for MicroSelectron the calculated transit dose is 7.9cGy with an agreement of 8%. Transit dose depends linearly with activity source and number of fractions, and increase with the number of catheters. As for ACE validation, the comparison with a TG-43 formalism for gynecological treatments doesn't show a significant difference in terms of doses received by 90% of PTV and by 2cc of OAR (bladder, bowel, rectum). For vaginal cases, the maximum difference is for bowel (3.2%) and for Fletcher case is for bladder (2.3%). In particular, the median of relative percentage difference for the vaginal case is smaller than 1%, and for Fletcher cases smaller than 2%. DVH analysis confirms the same trend.

**Conclusion.** The acceptance test shows that the status of the machine and its components are functioning well and the machine is ready for to be used in clinical practice. In order to enhance safety and reliability of high dose rate brachytherapy, above all for specific anatomical sites, dynamic dose calculations should be

integrated into all high dose rate TPS and not be assumed negligible. For gynecological treatments, ACE doesn't seem to add a significant improvement respect to TG-43 formalism. Some limitations were found in ACE since the user cannot modify the CT to density table; the user can only choose the method used by TPS to define electron mass density: uniformity density, that uses tabulated value in TG-186, or HU-based, that uses HU values according to the paper of KNÖÖS [19].



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**Title:**

## Validation of the ArcCheck diode array for the patient specific Quality Assurance in Stereotactic Body Radiotherapy Treatment (SBRT) delivered with VMAT

### Prospective/Objective:

Employment of cylindrical diode array for patient specific Quality Assurance (QA) in small fields used for Stereotactic Body Radiotherapy Treatment (SBRT) is still not clearly well stated and remain debatable. This is due to the dose map collected represents the projections of the 3D dose distribution on the target away from the isocentre. The cylindrical array detectors also have sparse low spatial resolution. The aim of this study was to evaluate the accuracy of the measured dose distribution by ArcCheck diode array (Sun Nuclear) in SBRT that demands extraordinary attention to Quality Assurance (QA) issues related to the high geometric and dosimetric accuracy.

**Materials and methods.** SBRT on 12 virtual spherical tumors of different radii ranging from 4mm to 15mm with an increment of 1mm on ArcCheck phantom were generated with volumetric modulated arc therapy (VMAT) and flattening filter free (FFF) with RayStation 5v5.01 (Raysearch) Treatment Planning System. All plans were delivered through Varian Trilogy TX Linac (6MV) on ArcCheck phantom consisting of a cylindrical array of diode detectors with MultiPlug™ homogeneous RW3 cylinder with a Gafchromic

EBT<sub>3</sub> film inserted in a coronal plane at the isocenter. The measurements were done for both standard (Sm) and high density (HDm) ArcCheck mode that creates a high-density measurement through double measurements using the shift markers on the ArcCheck phantom. Films were scanned using an EPSON 10000 XL flatbed scanner using a tool of MapCheck (Sun Nuclear) to convert the gray-level of the film to planar dose. Analysis of ArcCheck and films measurement was performed through local gamma index analysis, (%PASS) percentage of evaluated measurements points passing criteria of dose difference (D%) and the distance to agreement in mm (DTA).

We studied the passing rates in ArcCheck Sm, in HDm, in film and the dependence of the passing rates (%PASS) with the relevant parameters such as DTA and D% criteria used for QA and on the target volumes.

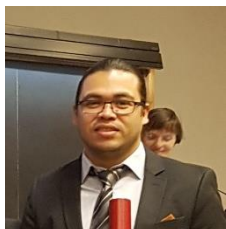
**Results.** The agreement between the calculated dose with the one measured by the EBT<sub>3</sub> film with the ICRU point for each target at isocenter was optimal with a dosimetric uncertainty below the 3%, considering that the uncertainty budget of dose

determination for EBT<sub>3</sub> film is close to 3%. The major influencing factor affecting the passing rate of the Gafchromic film is observed to be the DTA. A %PASS > 75% on whole film appeared as a predictor of a 90% passing rate in the target and peripheral region generally for the DTA:1mm and D% >3 criteria. The mean value of %PASS in HDm was slightly lower than in Sm. The difference between Sm and HDm tested was significant, but not clinically relevant. In Sm ArcCheck, DTA was the main prognostic factor for passing rate as expected for the high gradient SBRT dose distribution delivered at the isocenter. Although statistically significant, the correlation with the sphere volumes was weak. In the ArcCheck in Sm, similar passing rate (same sensitivity) could be obtained with different gamma criteria combinations. The standard criteria of gamma (DTA: 2mm, D%: 2) had passing rates similar to the gamma (DTA: 1mm, D%: 4). ArcCheck Sm passing rates were well correlated with the radiochromic film passing rates. The optimal level of agreement was found between the ArcCheck gamma (DTA: 1mm, D%:4) criteria and film gamma (DTA:1mm, D%:3) criteria. ArcCheck passing rates were biased by a small overestimation (about 3%, clinically negligible) and a level of agreement contained in 5%

**Conclusion.** These results showed optimal agreement and high accuracy level for the whole end to end test performed with the ArcCheck phantom and that ArcCheck Sun Nuclear phantom with measurements in standard

mode can be an adequate verification system for small fields in SBRT.

In SBRT where the geometric uncertainty is the major concern the criteria DTA 1 mm and D% 4 with a passing rates superior to 75% (threshold 20%) in ArcCheck can be more favorable to assess patient specific QA. Above this limit (action level), 90% of points in the target and in the dose falloff region met the DTA=1mm requirement on the Gafchromic EBT<sub>3</sub>.



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## Title: Angular dependency correction of a 3D dosimetry system for verification of Cyberknife® treatments

**Prospective/Objective:** Modern technologies applied in clinical practice such as volumetric modulated Arc Therapy (VMAT), Intensity-Modulated Radiation Therapy (IMRT), Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT) have the necessity to present an accurate delivery of dose, for this multiple ways for planning verification are applied nowadays result of which depends of the delivery complexity and machine used.

Different commercial 3D dosimetry systems are available for conventional flattened and flattened filter free (FFF) linacs, such as ArcCHECK®, Octavius 4D, Delta<sup>4</sup>, however the appropriateness of these systems is to be assessed for unconventional linacs e.g. Cyberknife® systems.

In Cyberknife® plan delivery, the treatment verification becomes more complex due to the inclusion of multiple entrances of non-coplanar beams and the steep gradients. Thus the performance of patient specific quality assurance (QA) systems developed for IMRT/VMAT treatments needs to be fully understood using.

The 3D dosimetry system Delta<sup>4</sup> (ScandiDos) is factory calibrated using a conventional Linac and

provided with an internal data base of correction coefficients depending on the irradiation geometry. For plan verification the Delta<sup>4</sup> software learns the plan irradiation geometry from a DICOM file (RTplan) provided by the Treatment Planning System (TPS). In Cyberknife treatments the beam geometry is potentially very different from conventional linac treatments and at the moment the dedicated TPS (Multiplan®) does not output an RTplan DICOM file readable by the Delta<sup>4</sup> system. The aim of this work is to provide means to fill this communication gap and to evaluate and characterize the Delta<sup>4</sup> dosimetry system for verification of Cyberknife® treatment delivery with particular care in the study of the angular response using multiple tests (irradiation setups) and a homemade MatLab code.

**Materials and methods.** Plans corresponding to reference beam directions made on Multiplan® using the largest fixed collimator and delivered on a Cyberknife® M6™ Series system, were selected to be verified on a the 3D system Delta<sup>4</sup> (ScandiDos) which consists of diode matrices in two orthogonal planes inserted in a cylindrical PMMA or Plastic Water phantom material that is 22 cm in diameter and 40 cm longitude, has 1069 p-Si detectors with distance in the central area (6x6 cm<sup>2</sup>) each 5



mm and in the outer area each 10 mm. Comparisons were performed between measured and calculated (given by the TPS) sagittal and coronal planar doses for each of the available beam directions of a SBRT treatment and maximal collimator size. A MatLab homemade code was used to extract the planar dose data from the planned distribution (taken as gold standard).

**Results.** A set of matrices of correction coefficients to be applied in the verification of a clinical plan was obtained. In the comparison between the calculated and measured dose of the clinical plan, performed in the sagittal and coronal detector planes, 71.8% of the irradiated diodes in the sagittal and coronal detector planes were within the 2% of Dose Difference (DD) when no correction is applied. Using the correction matrix this percentage raises to 83.1%.

### **Conclusion.**

The results obtained confirm the need to improve the performance of the Delta<sup>4</sup> system in the verification/evaluation of treatments performed with a Cyberknife<sup>®</sup> through the use of special correction matrices. With this correction in a treatment plan of low complexity (less than 30 nodes and only one collimator size) we have an almost 12% increase in the percentage of measurement where the agreement between calculated and measured dose is better than 2%.

In addition, the performance of the measurements shows an evident necessity of the inclusion of

internal and/or external fiducial markers on the Delta<sup>4</sup> phantom to avoid misalignment and unnecessary automatic positioning "corrections" performed by the Cyberknife<sup>®</sup> robot.



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**Title:**

## Verification of the physics model of the treatment planning system Pinnacle3 through Monte Carlo simulations.

**Prospective/Objective:** The main purpose of the present work was to verify the physical model in Pinnacle3 (TPS) in general and when a new treatment planning technique is implemented, by means of Monte Carlo (MC) simulations of a 6 MV photon beam, with the DOSXYZnrc and EGS\_chamber codes. For example, we wanted to verify the use of one isocenter in the 3DCRT for the treatment planning of breast and Supraclavicular (SC).

**Materials and methods.** Monte Carlo simulations of a 6 MV photon beam were performed by using EGSnrc MC codes. BEAMnrc code (1) was used to model an Elekta Synergy linear accelerator: the input file consisted of 8 component modules (CM), from the source to the lower diaphragms. The benchmark of the accelerator was done previously. The DOSXYZnrc code (2) was used to simulate percentage depth doses (PDD) and profiles (Off Axis Ratio) in a cubic water phantom. The MC data are then normalized and compared to the ones calculated with Pinnacle3 TPS. The egs\_chamber code (3) was used to simulate profiles obtained with a semiflex ion chamber, to compare with measurements. In particular, in the first stage, PDD and profiles of symmetric fields were simulated with DOSXYZnrc for several field sizes: 5cm x 5cm, 10cm x 10cm, 20cm x 20cm and 40cm x 40cm. In

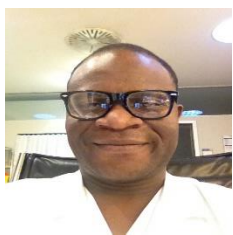
the second stage, asymmetric fields were also simulated: hemi fields from 0 to 2.5cm in X direction, for the 5cm x 5cm, and from 0 to 5cm for the 10cm x 10cm field etc. The largest fields were considered of interest because they are used clinically in the case of 3DCRT planning for breast with supraclavicular involvement

**Results.** Profiles of symmetric fields were analyzed and compared with the ones obtained from Pinnacle3 TPS. The uncertainties of MC simulations were less than 1% in the central field area and less than 2% in the penumbra region, the profiles of the two sets coincide within that uncertainty. In the second stage of this work, asymmetric profiles for the same set of field sizes were simulated. As shown in fig. 2, the profiles of simulated hemi-fields are in agreement with the ones obtained from TPS within the mentioned range of uncertainty for MC simulation.

**Conclusion.** When new planning technique is being used it is of importance and responsibility of the medical physicist to analyze how that technique is appropriate to the physics model provided by the TPS, since the model is always a compromise between measured data for different beam setups and beam sizes.

In this work, beam data for the simulated linac, were compared to

the ones from the TPS. Profiles related to clinical treatment planning technique 3DCRT breast+SC with one isocenter was simulated and analyzed. The shape of the profile of hemifields reflects the observed worsening at the border of the field in the longitudinal direction (Y), with a loss of dose coverage in treatment planning when a one isocenter technique is used compared to the two isocenters planning technique.



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### Title:

## Characterization of density model of the CT part of GE Discovery 710 PET/CT scanner using Gammex 467 phantom for MultiPlan Treatment Planning used in Cyberknife system

**Prospective/Objective:** It is estimated that there is about 30% error in prescription dose due to not correcting for tissue inhomogeneity. The use of prostheses and other life saving devices in the body is beneficial to patients but inability to correct for inhomogeneity in densities of these materials could account for in treatment planning process, big errors could result in a mistreatment or even death.

The purpose of the work is to characterize the density model of the CT part of the PET/CT using Gammex 467 phantom to be used in MultiPlan Treatment system used in CyberKnife System.

**Materials and methods.** Gammex 467 phantom with 16 different material inserts was scanned using GE Discovery 710 PET/CZ scanner using body protocol at 120 kVp. A second scan was performed after replacing one insert with Titanium insert. The images were downloaded and analyzed with ImageJ software. Regions of Interest (ROIs) were drawn on the central position of the different material inserts of the axial images and mean CT numbers and their standard deviation were estimated/determined. The mean CT numbers were plotted against the relative electron density and mass density of the insert materials are provided by the Gammex manufacturer. Linear interpolation

was done between the highest CT numbers from the scan without Titanium insert and the CT number of Titanium. The maximum permissible relative electron density and mass density and their corresponding CT numbers were fitted into the curve. The resulting CT numbers and the relative electron densities and mass density were then entered into the Treatment Planning System.

### Result.

The mean CT numbers determined ranged from  $330 \pm 46$  HU to  $2180 \pm 28$  HU for the lung 300 to the Cortical bone inserts and a value of  $4050 \pm 120$  HU for the Titanium insert. A linear interpolation links two curves are plotted for CT number /mass density and CT number/ relative density model. The mass density model represents materials of mass densities from 0.31 to 1.823 and their corresponding CT numbers from 330 to 2180. The linear interpolation shows the link between the cortical bone with density of 1.823 and mass density of Titanium which is 4.59 and corresponding CT number of 4050. The TPS allows maximum mass density of  $2.65 \text{ g/cm}^3$  which corresponds to CT number of 2737. If density model characterization is not performed with Titanium insert and a patient with metallic prostheses is scanned for planning, the TPS assigns cortical bone density as the limit even if the

prostheses is of higher mass density.

If a tissue characterization is however performed of Gammex 467 with Titanium insert and modelled in to the TPS, the system forced to assigned a higher mass density limit of 2.65 to any prosthetic material of CT number equal or higher than 2737. Meaning that with Titanium prosthesis the TPS will assign a limit mass density of 2.65.

The electron density model represents materials of relative electron densities from 0.304 to 1.695 and their corresponding CT numbers from 330 to 2180. The linear interpolation between the cortical bone with density of 1.695 and electron density of Titanium, which is 3.79 and corresponding, Titanium CT number of 4050.

## Conclusion

For accurate dose calculations, it is necessary to provide a correct relationship between the CT numbers and mass and electron densities in radiotherapy treatment planning systems (TPSs). The PET/CT is now used in Radiotherapy treatment planning in many centres hence there is a need to characterize their density models to deliver accurate doses with maximum curative effects to the target minimizing harm to normal surrounding tissues.



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#### Title:

## Quantification of Transit Time of High Dose Rate Brachytherapy $^{192}\text{Ir}$ Stepping Source-Transit Dosimetry

**Prospective/Objective:** To quantify the interwell transit time of HDR brachytherapy treatment unit and to gain insights into the accuracy of brachytherapy treatment and the quality controls

**Materials and methods.** Transit time was determined from a linear regression analysis of measured charge as a function of dwell time. In this investigation a Dosimetry Systems comprising of a PTW Well-type ionization chamber model 077094 and electrometer PTW UNIDOS Webline model T10021 was used to measure charge generated during source dwelling to pre-programmed position and during transit. The brachytherapy machine used was a Nucletron microselectron-HDR v3.

**Results.** The average transit time was found to be 0.90 and 0.94, seconds respectively by linear regression analysis and multiple exposure method. The average standard deviations were 0.01 seconds and 0.03 seconds respectively. The average speed of the source was found to be 41cm/second, while the average time for source to travel 1cm was found to be 0.02 second.

**Conclusion.** This was investigative study to quantify the transit time of HDR Brachytherapy unit. It showed good agreement of calculated interwell transit time between the two methods. It highlights the importance of quality control as a

tool to check against transit dose to patients. This procedure has the potential to be utilized for routine quality assurance and Quality control check of the interwell position transit time of any remote after-loading HDR brachytherapy source and during commissioning.



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**Title:**

## Radiochromic Film Dosimetry for Output Factors in Intraoperative Radiotherapy

**Prospective/Objective:** The present work aims at investigating the output factors of Mobetron 2000, a dedicated mobile LINAC for IORT used in CRO hospital, with radiochromic films, because of their weak energy dependence and high spatial resolution. Then the history and properties of the dosimeter chosen to characterize the electron energy of this machine, radiochromic films, are described. The output factors measured with gafchromic EBT<sub>3</sub> are compared with values obtained with stereotactic field diode at the time of commissioning of the machine. The second aim of the work was to determine if the presence of tissue heterogeneities such as bone can influence measured doses in vivo. For this purpose, measurements in water with radiochromic films in presence of an insert of density equivalent to that of cortical bone were performed.

**Materials and methods.** For calibration of Gafchromic EBT<sub>3</sub> films, these were irradiated with electron beam of 6, 9, and 12 MeV, the same beam qualities of the Mobetron 2000, delivered by a 2100C/D Varian conventional LINAC. The films were scanned using a flatbed document scanner in RGB mode. The calibration curves for each energy were obtained by fitting a polynomial equation as described by Devic et al dosimetry protocol. The output factors were measured with EBT<sub>3</sub>

at depth of maximum dose on the clinical axis, for applicators of different sizes, with 0°, 15° and 30° angles and normalized to 10 cm diameter 0° beveled applicator. The results were compared with those obtained with stereotactic field diode and Advanced Markus ion chamber that were performed at the time of commissioning of Mobetron 2000 unit.

Additionally, a dose measurement was also performed in water with EBT<sub>3</sub> attached to a small cylindrical phantom of density equivalent to the density of cortical bone in order to assess if the presence of bony structure (in case of soft tissue sarcoma of extremities) influences the measured in vivo dose.

**Results and Conclusion.** The output factors measured with Advanced Markus plane parallel chamber were equivalent to Gafchromic EBT<sub>3</sub> films for 0° beveled applicators. Significant difference resulted in the output factors in some cases (up to 6%) as measured by EBT<sub>3</sub> films when compared to stereotactic diode results. Thus, for output factor measurements for Mobetron 2000, radiochromic films can be considered as the reference detector because of the negligible thickness, high spatial resolution, and low energy dependence of response. Moreover, the study showed that the presence of bones in the irradiated region in IORT can increase dose readings in vivo, e.g. for treatments of extremities, up to

3.7% increase in output factor was resulted when measurement was performed with a phantom material having density equivalent to that of cortical bone.





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### Title:

## Verification of the Implementation of Enhanced Dynamic Wedge in the Treatment Planning System Eclipse before use in clinic.

**Prospective/Objective:** The objective of the study is to verify the implementation of the Enhanced Dynamic Wedge (EDW) before the use in clinical operation in the Treatment Planning System Eclipse model 13.6 of the Varian Company.

**Materials and methods.** This was done by comparing the dose calculated by the TPS and the measurement according to the TRS-430. Dose was calculated with the AAA (Anisotropic Analytical Algorithm). The Linac used was the model 2100 CD of the Varian. PDD, absolute dose and Dose distribution along the field was measured. All the measurement was simulated with the TPS and same setup was established for both. Absolute dose was measured using the FC65G and the A14SL Ionization Chamber (IC) with a collective volume of 0.6 [cm]<sup>3</sup> (more than 4×4 cm<sup>2</sup>) and 0.009 cm<sup>3</sup> (less than 3×3 cm<sup>2</sup>) for all possible setup that can be met during a radiotherapy treatment: square, rectangular, off-axis field with Y<sub>1</sub>-in and Y<sub>2</sub>-out with different wedge angle. Absolute Dose difference was calculated by  $[(\text{measured} - \text{calculated}) / \text{measured}] \times 100$  , and was evaluated with a dose difference (DD) of 2%. For small field an attempt with Gafchromic film was done to measure the absolute dose, film was scanned with the Epson flatbed scanner,

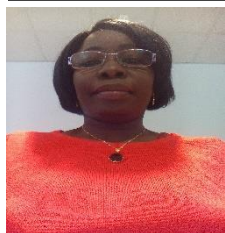
conversion optical density to dose was done with Matlab. Dose distribution along the field was checked using the Delta4 phantom manufactured by Scandidos and was evaluated using 2% DD, DTA of 2 mm (Distance To Agreement), and also gamma analysis was used to analyze the whole distribution: 2% DD and DTA of 2 mm. PDD was measured with the IC model CC13 with a collective volume of 0.13 cm<sup>3</sup> with a step of 2 mm from the surface to 2 cm depth and beyond d<sub>max</sub> with a step of 5 cm till 30 cm depth and was also evaluated with a DTA of 2 mm in the buildup region to have better resolution and with DTA of 2 mm and 2% DD beyond the buildup region.

**Results.** Absolute dosimetry with Gafchromic associates a discrepancy of 5%. Absolute dosimetry with IC was all less than 2%. For the PDD measurement the criteria was all met (2mm DTA in the buildup region, 2% DD and 2mm DTA beyond the buildup region). All dose distribution along the field satisfies the criteria (2 mm DTA in gradient region, 2% DD in the flat region of the field). For PDD and dose distribution, a disagreement for DD in the gradient region was found.

### Conclusion.

Good agreement with the measured and calculated dose was obtained. TPS models the EDW with good accuracy. 3D conformal radiotherapy with EDW is very fast

to plan and could be a good solution for a busy radiotherapy clinic. The EDW in this linac satisfy the dosimetry criteria and can be used in the clinical routine.



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## Title:

# IMRT and VMAT patient's pre-treatment quality assurance using Electronic Portal Imaging Device (EPID) dosimetry

**Prospective/Objective:** Pre-treatment verification can discover the possible difference between the planned dose and the actual delivered dose. To evaluate the influence of the differences between planned and delivered photon beams, a 3D dose verification method has been developed that reconstructs the dose inside a phantom. The pre-treatment procedure is based on portal dose images measured with an EPID. The converted EPID dose distribution can be compared to dose calculation from the Treatment Planning System (TPS). A Quality Assurance (QA) program for IMRT and VMAT verification with an electronic portal imaging device, has been doing for 5 years (2013-2017). The goal of the present work is to discover a potential relationship between pre-treatment verification results and different irradiation parameters in order to understand whether the plan complexity can influence the QA outcome. As an additional investigation, QA tests ability to find out possible delivery error was studied, by introducing voluntary modification in the total monitor unit number.

**Materials and methods.** A total of 1147 VMAT and 520 IMRT cases (including prostate, head and neck, breast, brain, lung, pelvis, mediastinum) were enrolled on a pre-treatment verification using EPID. For VMAT plans 711 patients were treated with energy 6MV and

436 patients with 10MV. For IMRT plans 310 patients were treated with 6MV and 210 patients with 10MV. All plans were optimized and calculated with Monaco version (5.11.0.1) and Oncentra version (4.3) treatment planning systems respectively for the two techniques.

Patient's QA plans were calculated too and the Elekta EPID iViewGT were used to verify the dose and the measurements were performed with two Elekta linear accelerators Synergy and Synergy S equipped with multileaf collimators. In order to compare the measured dose and the computed dose, the EPIDose software with gamma evaluation analysis (3%-3mm) was used.

**Results.** Over 1147 VMAT analyzed patients' plans the average passing rates were  $97.23\% \pm 3.61\%$  and  $95.25\% \pm 3.75\%$  for 6MV and 10MV respectively and over 520 IMRT analyzed patients' plans average passing rates were  $99.04\% \pm 2.05\%$  and  $97.07\% \pm 2.81\%$  for 6MV and 10MV respectively.

The results showed that the average passing rates of the points pass the gamma criteria for both VMAT and IMRT.

The relationship between passing rate and the other variables was investigated but no correlations were found

A simulated error was also done to see how EPID is a useful tool for detection of errors during pre-treatment verification. And the

results of this simulating showed a difference between the passing rate (95.3%) of the original plan to the passing rate (63.1%) of the plan where an under dosage was observed with gamma criterion of 3%-3mm.

**Conclusion.** The use of EPID is adequate for pre-treatment verification technique. The benefit of using the EPID is to its potential for high accuracy, large active area, and high resolution to intercept clinically relevant dosimetric errors prior to the beginning of treatments.



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#### Title:

## Radiation Therapy Techniques and Treatment Planning for Breast Cancer.

**Prospective/Objective:** The treatment of breast cancer involves a multi-disciplinary approach with radiation therapy playing a key role. Along the years different techniques were used beginning with conventional 2D radiation therapy techniques to 3D radiation therapy (3DCRT) and more precise yet expensive, Intensity modulated radiation therapy (IMRT) and the newest technique VMAT (volumetric radiation therapy). The aim of this study is to determine and compare the dosimetric parameters of PTV and organs at risk for the breast irradiation among the three planning techniques 3DCRT, IMRT and VMAT.

**Materials and methods.** Two right and two left-sided breast cancer patients were selected; we divided all patients into two categories: Group-I (patient-1, -2) breast only and Group- II (patient-3, -4) breast and supraclavicular area. Dose prescription was 50 Gy to the PTV, 25 fractions of 2Gy in each fraction. The virtual simulation images of these patients were used to generate 3DCRT, IMRT and VMAT plans by Varian Eclipse (V. 10.0.34). Dose

volume histograms were generated for 3DCRT, IMRT, and VMAT plans and various dosimetric parameters such as Dmax, Dmean, Dmin, D2%, D98%, V95%, V107%, Conformity Index (CI), Homogeneity Index (HI) and Uniformity Index (UI) for the PTV and dose to ipsilateral lung,

contralateral lung, heart, contralateral breast and also body were calculated. The patient quality assurance for IMRT and VMAT plans performed by gamma analysis. The 3mm DTA & 3% and 2mm DTA & 2% dose difference of the global Gamma Index ( $\gamma \leq 1$ ) were used for the analysis.

**Results.** The CI, HI and UI were significantly better for IMRT and VMAT compared to 3DCRT and also there was minor difference between IMRT and VMAT for both groups. The Dmin was higher for VMAT than IMRT and 3DCRT for both groups. The V95% and

V107% as well as for D2%, D98% were better of IMRT techniques than 3DCRT and VMAT plans for both groups. The maximum and mean lungs and heart dose were higher with VMAT and IMRT compared to 3DCRT for both groups. The volume of ipsilateral lung and heart receiving 5 Gy and 10 Gy were higher for VMAT for both groups. The mean dose to contra lateral breast, lungs and body were similar for IMRT and 3DCRT, but higher with VMAT. For global gamma analysis, the gamma passing rate (%GP) in the criteria of 3%/3 mm exhibited above 95% but the 2%/2 mm exhibited above 91% for IMRT and VMAT plans of both groups.

**Conclusion.** Newer modalities of breast irradiation such as IMRT and VMAT appear to provide better dose coverage, conformity, homogeneity and uniformity to

complex PTV. 3DCRT showed dosimetric benefit in standard breast cancer, IMRT & VMAT combined the advantages of good target coverage and homogeneity, reduction of high-dose volumes in organ at risk and a modestly higher dose to adjacent healthy tissues. In future, the breath hold technique should also be considered because of the significant reduction in radiation dose to the heart compared with free breathing technique for left breast radiotherapy.



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## Title:

# Evaluation of EPIDose™ and Dosimetry Check™ for EPID based dosimetry

**Prospective/Objective:** To optimize the EPIDose™ parameters to improve the accuracy of dose reconstruction with this software as a RapidArc pre-treatment quality assurance tool. To evaluate the versatility of Dosimetry Check™ as a pre-treatment quality assurance tool, and as an in-vivo tool for RapidArc™ plans. And to verify the EPID response stability as well as its mechanical alignment to ensure the robustness of these quality assurance methodologies.

**Materials and methods.** The PortalVision aS500 EPID, attached to a Varian Clinac DHX linear accelerator, was used for EPIDose™ optimization and Dosimetry Check™ evaluation. The effect of image calibration and change in dose rate in the EPID response was analyzed. The EPIDose™ physics model was optimized by searching the best fit between the treatment planning system calculations to EPIDose™ calculations while varying the redistribution kernel and the Dose/EPID Ratio MLC Transmission parameter.

Dosimetry Check™ was evaluated in-air and in-transit mode. Open and modulated arc fields were tested in a homogeneous phantom and in the patient's CT scans. In the homogeneous phantom, additional tests with the gantry reset to 0° were performed to compare the results to those obtained with EPIDose™.

**Results.** EPID image calibration changed the CAX response; increasing 0.6% after DF and FF calibration, and decreasing 0.5% for a change in the dose rate. The EPID shifts in the lateral and longitudinal directions were smaller than 3~mm. The optimized EPIDose™ physics model planar doses are in well agreement to TPS calculations, with an average two dimensional gamma passing rate of 97.0% +/- 1.8% for twelve plans analyzed. Dosimetry Check™ in-air and in-transit with the homogeneous phantom overestimates the dose around 2%, compared to treatment planning system calculations. Dosimetry Check™ in-transit mode produced dose differences in head and neck cases up to 15%, while in rectum and metastasis cases up to 10%, which is reflected in the decreasing and spreading of the gamma passing rates as compared to the pre-treatment case.

**Conclusion.** EPID image calibration changed the CAX response; increasing 0.6% after DF and FF calibration, and decreasing 0.5% for a change in the dose rate. The EPID shifts in the lateral and longitudinal directions were smaller than 3~mm. The optimized EPIDose™ physics model planar doses are in well agreement to TPS calculations, with an average two dimensional gamma passing rate of 97.0% +/- 1.8% for twelve plans analyzed.



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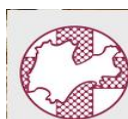
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**Title:**

**Two dimensional ionization chamber array: characterization and clinical applications**

**Prospective/Objective:** Ionization chamber array is nowadays the standard tool for pre-treatment verification of radiation therapy complex planning (VMAT). It is therefore imperative to characterize such systems. The aim of this work is to evaluate the response of the PTW 2D Array seven29 detector in terms of reproducibility, linearity, percentage depth dose, output factor and directional dependence for photon beams.

**Materials and methods.** The PTW 2D Array seven29 consists of a matrix of 729 cubic vented ionization chambers with 0.5 cm × 0.5 cm cross section, spaced 1 cm center-to-center, giving a total area of 27 cm × 27 cm. Pinpoint ionization chamber (model 31016) was used, and also the RW<sub>3</sub> slab designed for high energy radiation therapy dosimetry. For direction (angular) dependence, Elekta Monaco (version 5.11) treatment planning system was used, which is a Monte Carlo-based treatment planning system. The statistical analysis throughout this thesis was done with PTW Verisoft software (version 6.1) and Excel 2007 in order to evaluate all the results. The measurements were done with Elekta Synergy linear accelerator. All the readings for PTW 2D array were taken according to the central axis (CAX) ionization chamber. The fields size used are between (2x2 cm<sup>2</sup> until 25x25 cm<sup>2</sup> ) with different monitor units (2 to 500

MU), and different energy photon beams (4 MV and 6 MV) depends on what every measurement needs.

**Results.** The reproducibility of the measurements in 10x10cm<sup>2</sup> within each batch is good with a value of the standard deviation of the mean not exceeding 0.2%. The PTW 2D Array shows a perfect linear dependency to the monitor units delivered in the range 2 - 500 MU, with R<sub>2</sub>=1. We determined the effective point of measurement (EPM) by comparison between percentage depth dose curves on the CAX of PTW 2D Array with PinPoint ionization chamber, we found that PTW 2D array adjusts at 8 mm comparing with EPM of PinPoint (5 mm) as a reference, which give us a difference of 3 mm. The output factor results to a good agreement between our two devices with maximum deviation of 1%. For directional response evaluation the difference between the measured and calculated dose within the 2D Array was calculated, and the difference between the total dose given to the central detector and expected was 1.2% when the 2D Array was scanned in the OCTAVIUS phantom (Air), and was 0.9% when the ionization chambers are considered as filled by water, by forcing the electron density to 1 (Dens).

**Conclusion.** PTW 2D Array seven29 is a very reliable, accurate, fast and precise tool for pre-treatment verification of radiation therapy complex planning (VMAT).



It's a useful device for QA and patient specific pre-treatment radiotherapy plan verification in clinical settings.



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**Title:**

**Out of field dose in radiation therapy planning: evaluation and measurements in clinical cases**

**Prospective/Objective:** New radiation therapy techniques greatly improved our ability to deliver higher tumor doses while minimizing the dose to the adjacent organs at risk. This improved conformality has not mitigated the problem of doses to normal tissues outside the treated volume. Out-of-field doses are mostly due to photons, electrons from linac head (jaws, multi-leaf collimator, shielding), patient and table. That scattered radiation can cause detrimental health effect, such as cataract for eye lens and dysfunction of cardiac implantable electronic devices (CIED). In this study we evaluate out-of-field dose with two different dosimeters, thermoluminescence dosimeter (TLD) and film, considering two applications: the estimation of eye lens dose and the estimation of dose to the pacemaker at different distances from beam edge.

**Materials and methods.** Firstly, TLD and film were evaluated for out-of-field dose measurements and compared with ion chamber ones, in a fixed 20x20 cm<sup>2</sup> field. Secondly, VMAT and SRS/SBRT plans were generated on Elekta MONACO Treatment Planning System (TPS) and recalculated on the Alderson RANDO phantom, as a part of the QA program. We considered 6MV VMAT plans: for the "eye lens case": treatment on the brain and rhinopharynx, and for the "pacemaker case": treatment on breast, lung and neck. The out-

of-field doses were calculated at different distances from field edge in the cranio-caudal direction. For the "pacemaker case" we measured the dose with the dosimeters placed on phantom surface. For the "eye lens case" we compared dosimeters measurements with the TPS calculations. The clinical impact of out-of-field doses for both cases were investigated according to AAPM TG-158 protocol.

**Results.** TLD and film are in good agreement with the ion chamber, within  $\pm 1\%$  dose difference with respect to the central axis dose. Pacemaker dose decreases with distance from field edge and depends on the Planning Target Volume (PTV). In the "eye lens case" TPS overestimates the dose at field edge (3% - 7% of the prescription dose) and underestimates it after 1 cm (-1.5% - -0.5% of the prescription dose). We estimate a safe distance of 3cm for low risk pacemaker dose and eye lenses cataract disease for the evaluated plans.

**Conclusion.** TLD and film dosimeters are suitable for out-of-field measurements. Dose to the pacemaker depends both on PTV volume and beam edge distance, so in vivo dosimetry is preferred for accurate evaluation, especially for the high clinical risk patients. TPS overestimates the out-of-field doses below 1.5cm from field edge comparing with the measurements, while it

underestimates the out-of-field doses after that. By normalising calculated and measured doses by prescription dose, the underestimation will be less than 2%.

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**Title:**

**Analysis of Set-up Uncertainties and Organ Motion in Prostate Radiotherapy Based on Day to Day CBCT Verification**

**Prospective/Objective:** The basic goal of this thesis is to propose an optimal definition of PTV evaluating setup and organ motion uncertainties for prostate tumor.

**Materials and methods.** For the development of this work we have considered selection of the patients made from the database from January to April 2017. Thirty-three patients with adenocarcinoma of the prostate staged T<sub>1</sub> to T<sub>4</sub>, treated using volumetric modulated arc therapy (VMAT), were evaluated.

The evaluation of systematic and random errors was performed using image registration between daily Cone Beam Computed Tomography (CBCT) and CT used for planning. Bone anatomy was used as fiducial marker for setup and gold seeds implanted within the prostate as fiducial markers for organ motion. To perform the analysis, the displacement between registered bone position and laser position was listed for setup and between registered gold seed and registered bone position for organ motion.

**Results.** Matching of two scans with about 60 slices of 256 x 256 pixels takes about 2 min on a workstation and achieves subpixel registration accuracy. Matching of the organ contours takes about 30 s. The accuracy in determining the relative setup movement and organ motion was 0.9 to 1.5 mm

and 0.3 to 0.9 mm, respectively. From the analysis of setup errors and organ motion, an optimized margin was obtained to define the PTV from CTV: 4.4 mm in the anterior-posterior direction, 3.3 mm in the cranio-caudal direction, 3.7 mm in the lateral-lateral direction.

**Conclusion.** Cone Beam CT is an accurate and precise tool for image guidance that provides many useful information: in this study CBCT was used only to evaluate bone and gold seeds position but the 3D images make it possible to evaluate in the same time all other modifications within the patient and help the physician to take a decision in case of doubt.



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**Title:**

## Feasibility of the commissioning of a Radiotherapy treatment planning system focusing on multileaf collimator dosimetric properties using GAFchromic films.

**Prospective/Objective:** To characterize a treatment planning system (RayStation 6) supplied with data measured with a radiochromic film dosimetry system, for the improved modeling of the dosimetric parameters of multileaf collimators. Ionization chambers are usually used to measure data from the radiation machine to supply the TPS. However, these dosimeters are no longer appropriate for the measurements of small fields as they do not describe accurately the penumbra region. This work uses dosimetric information for open fields measured with Gafchromic film, which allowed a better definition of the penumbra region in the TPS.

**Materials and methods.** The data was acquired using a UNIQUE 6MV single energy photon accelerator with Millenium MLC-120 leaf model. GAFchromic film and DoseLab software were used for film characterization and processing, as well as for the profile acquisition. Measurements at different depths were done for open fields, one set of data for fields collimated with jaws and the other set for fields shaped with MLCs. Due to the size of the radiochromic films, information from fields larger than  $15\text{cm} \times 15\text{cm}$  were obtained from existing measurements performed with a water tank and semiflex chamber

for previous commissioning of the machine. The required profiles were extracted from the measured dose distributions in order to supply the radiation treatment planning system. Three beam models were characterized, one with information acquired for jaws collimated fields and two for MLC shaped fields. The MLC shaped models vary among them only in the values of the leaf tip width. Calculations and comparisons for validation of the models inside the Beam 3D module of RayStation 6 were made. Beam calculation and clinical verifications were made using field tests, patient QA tests and gamma analysis.

These test were carried out using two methods, the first using GAFchromic film and DoseLab, and the second one using ArcCheck and SNC, which are used for routine QA tests. Acquisition and validation tests were followed according to literature.

**Results.** The difference between delivered and computed field sizes is less than 2mm for the three models. The penumbra was modeled more accurately within less of 1 mm due to the high spatial resolution of GAFchromic film. Gamma analysis results for the models line within the criteria of acceptability.

**Conclusion.** The modeling of the penumbra region in the three models was improved when using

GAFCHROMIC™EBT<sub>3</sub> sheets than with a semiflex chamber. Moreover, the third proposed model shows the best agreement among them in the penumbra region. The results of this work suggest that the use of Gafchromic films for the commissioning of MLC dosimetric properties is feasible, even though it is time consuming. With more time invested, further work on the optimization of MLC parameters, as well as more verifications tests could be carried out.



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**Title:**

**Comparison between Analytical Anisotropic Algorithm and Collapsed Cone Convolution in 3DCRT and VMAT modalities for Lung Region**

**Prospective/Objective:** This work has the purpose to study the dosimetric differences between Analytical Anisotropic Algorithm implemented into Eclipse™ TPS (Varian Medical Systems, Palo Alto, CA, USA) and Collapsed Cone Convolution from RayStation™ (RaySearch Laboratories), in 3DCRT and VMAT modalities. They are applied to lung region, using gamma index 3D evaluation between dose map distribution calculated for both TPS, and gamma index 2D evaluation for dose map distribution, calculated for both TPS and compared to gafchromic films.

**Materials and methods.** In this study nineteen lung cancer patients were selected, 9 with 3DCRT and 10 with VMAT plans, all of them previously treated using Eclipse TPS. The plans were exported to RayStation TPS and new plans were calculated for a 6-MV photon beam on a Clinac® DHX linear accelerator (Varian Medical Systems, Palo Alto, CA, USA). Also, verification plans were created in an anthropomorphic phantom, in both Eclipse™ and RayStation™ TPS. Gamma index 3D evaluation was performed in PTW MEPHYSTO® VeriSoft Patient Plan Verification at 2%/3mm and 3%/3mm, after that, a subgroup of five patients, two for 3D and three for VMAT were selected for measurements using

GAFCHROMIC® EBT2 Dosimetry Film.

**Results and Conclusion.** From 2D gamma evaluation it was obtained that AAA has a better agreement with irradiated gafchromic films in comparison with the results obtained when dose distribution computed by CCC was evaluated. The best outcomes for gamma evaluation were found for VMAT plans, compared with 3D technique. Applying 3%/3mm criteria, the following results were obtained: 95.6% (patient 2) and 94.6% (patient 5) agreement for 3D modality – AAA; 95.2% and 89.0%, respectively, with CCC. For VMAT plans, the gamma evaluation for AAA with 3%/3mm criteria, for patients g, h and i, was 99.1%, 94.8% and 98.8%, respectively; for CCC the gamma passing rates were 98%, 90.5% and 90.6%, respectively. The failed points during gamma evaluation were observed in the lung region. Through this study a good estimation of the algorithms behavior in inhomogeneous regions was achieved, but it is recommended to perform more verifications using gafchromic films.



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**Title:**

## Evaluation of a commercial orthopedic metal artefact reduction tool in radiation therapy

**Prospective/Objective:** Computed Tomography images in radiation therapy are used for localize the planning target volume (PTV), the organs at risk (OARs) and calculate the dose distribution by treatment planning system (TPS). Image artifacts could lead either a wrong definition of structure contours by the clinician either an erroneous computation of dose due to inaccuracies in the Hounsfield Unit (HU) values. Radiotherapy patients often have metal implants and this causes several image artifacts. This study focused on the advantages using a commercial metal artifacts reduction algorithm, O-MAR (Philips Healthcare System, Cleveland, OH) and its effect on dose calculation.

**Materials and methods.** The study five head and neck cases were considered with metal dental implants. Patients were scanned on a large bore CT Brilliance Philips. The scanned images were reconstructed with standard and O-MAR algorithm for each patient. The structures drawing by the clinicians on the O-MAR series were copied on the originally CT images to evaluate the dose distribution on the same volume. Plans were performed on Pinnacle TPS with intensity modulated radiation therapy technique (IMRT). The treatment provided two or three PTVs, respectively with 54/66 Gy and 54/60/66 Gy and dose were evaluated on different OARs, close to the artifacts region,

such as bone marrow, parotids, mandible. Hounsfield Units (HU) variation were analyzed also in additional region of interest (ROI) near the dental implant.

**Results.** In OMAR images, noise value is reduced, standard deviation of HU is lower than in standard reconstructed images. Statistical analysis on HU values was performed, but no significant difference between the two data sets was founded. Evaluating the dose distribution and the dose volume histogram (DVH) with the physicians, no significant differences were detected by a clinical point of view.

**Conclusion.** In head and neck case, when patients have dental implants, the use of O-MAR improve the entire radiation treatment planning process, especially for contouring because increase the accuracy of CT HU and reduce the noise. No significant changes in dose calculation were founded.



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**Title:**

## Adaptive Radiotherapy in Lung Cancer: Dosimetric and Clinical Aspects

**Prospective/Objective:** The aim of this study is to evaluate if the standard ITV (Internal Target Volume) which was adopted by a physician for patients have lung cancer, has a sufficient margin to maintain an optimal coverage of GTV (Gross Target Volume) during all treatment course.

**Materials and methods.** 7 patients have adenocarcinoma lung cancer were selected for this study, they were treated at the Department of Radiation Oncology between 2013 and 2014. GTV and CTV were contoured by the specialist and a non-personalized ITV was defined (with an expansion of 1cm in cranial-caudal direction and 0.5 cm in other direction from CTV). For each patient 3D planning was available and several CBCT (from 7 to 9, that means about a CBCT every 3 fractions).

By using MIM- MAESTRO software (MIM Soft-ware, Inc., Cleveland, OH, USA) the physician propagated GTV and PTV contours from pCT (CT of planning) to each CBCT, then he corrected them manually. We superimposed new contours on pCT and on planned dose for each CBCT. The we evaluated the mean deviation of the volume and GTV coverage. Also to obtain accumulated DVH we used MIM software; first we generated deformed dose and contours of pCT on CBCT, then we propagated contours and dose from the planned CT to the last CBCT. In this case we verify and accepted deformable registration

of CBCT and structures and automatic propagation of doses and structures.

**Results.** For what concerns GTV volume which defined by the physician, we observed that in 3 of 7 cases had a percentage significant difference between pCT and mean values obtained from CBCT, so only in these cases it could be useful to replan. To decide if replan might be necessary we evaluated mean coverage of GTV related to pCT (we considered the 95% of prescription dose). All percentage difference is less than 3%. This data was also confirmed by accumulated DVH, 6 of 7 cases had the difference in coverage less than 2%; only in for one patient it was around 3%, but for PTV these differences in the coverage were less than 5%.

**Conclusion.** The mean difference within pCT of GTV's coverage obtained by superimposition of deformed contours by physician is in line with results obtained automatically in accumulated DVH by MIM. This means that we could be confident in deformable registration and propagation of MIM automatic workflow. We could say that CBCT set up verification and correction for these kinds of patients is enough to control GTV coverage. This is due to the fact that the security margin adopted for standard ITV is corrected. In adenocarcinoma lung cancer adaptive radiotherapy couldn't be necessary.



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**Title:**

**Experimental Measurements for the Implementation of Total Body Irradiation with Modulated Arc Beam**

**Prospective/Objective:** The aim of these experimental measurements was to implement a modulated arc technique for treatment with Total Body Irradiation (TBI), to be performed in a standard treatment room, with a 6MV Elekta Versa Linac, without any additional equipment.

**Materials and methods.** The measurements were performed with a PMMA solid phantom of 30x90x20cm<sup>3</sup>, and a Farmer type ionization chamber. The characterization of the profile parallel to the direction gantry rotation, generated by an arc between 290° and 70° using a field size of 40x40cm<sup>2</sup>, was the first beam data measurement; in order to provide a modulated arc beam, the individual contribution and weighting factors of each sub-arc were determined. Profiles acquisition in 'Entrance' and 'Exit' and transverse profile were acquired to estimate the dose at patient's skin and transversal homogeneity. The relation between the doses for different thicknesses of the phantom in 'Entrance', 'Mid-Plane' (prescription) and 'Exit' were evaluated.

The acquisition of the PDD curve for TBI setup was performed. The dose valuation of the attenuation of lead shielding blocks in homogeneous and nonhomogeneous medium; and how their presence affects the profile was studied.

In-Vivo dosimetry was performed with diodes, which were calibrated, validated and implemented through dedicated software PTW - VivoSoft. After the determination of all technical and dosimetric parameters, measurements and analysis, a procedure of the process was created and a complete validation of the arc technique was performed.

**Results.** The theoretical curves proved to be accurate in the prediction of the weighing factors for the determination of modulated arcs, with arc dose homogeneity of 2,3% in the L-R profile. The homogeneity derived from the measurements in the phantom surfaces (representative of the patient's skin) was of +7,06% with respect to the CAX and +7,11% with respect to the prescription mid-plane; the maximum variation in homogeneity of the transversal profile was of 3,48%. According to the study of the variation of dose for different phantom thicknesses, in 'Entrance', 'Mid-Plane' and 'Exit' positions, the expected linear and exponential decreasing behaviors respectively were obtained. The PDD curve in TBI conditions obtained was fitted to a second grade polynomial equation from where the values of PDD needed to calculate the calibration factors (CF) for the theoretical estimation of the mid-plane dose were obtained. The presence of lead shielding blocks attenuates the dose with a quadratic behaviour respect to its thickness; the

blurring effect is present in the profile, the penumbra in the L-R direction causes over and under-dosage, that must be taken into account for the shielding design. During the validation process, the measurements performed for different phantom thicknesses/homogeneities and in the anthropomorphic phantom for different procedure implementations were satisfactory.

**Conclusion.** Arc therapy is not only a convenient and robust method for the implementation of TBI technique but also easily applicable in a standard treatment room; guaranteeing an optimal dose homogeneity throughout the body, comfort and reproducibility of the patient's position and fast irradiation. In-Vivo dosimetry was successfully implemented, the use of PTW-VivoSoft provide a quick and visual tool of the dose measurements during the irradiation, allowing the detection of errors or changes, which may lead to dose correction or adjustment to the prescribed dose of the patient.



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#### Title:

## Evaluation of performance parameters of the new Philips Ingenuity TF PET/CT scanner.

**Prospective/Objective:** To evaluate the performance characteristic of Philips Ingenuity TF PET/CT system (Philips Healthcare, Cleveland, OH, USA) of both PET and CT parts. A comparison of different image reconstruction protocols for EARL FDG-PET/CT accreditation programme (European Association for Nuclear Medicine Research, Ltd) was also performed.

**Materials and methods.** Philips Ingenuity TF is a hybrid PET/CT scanner equipped with LYSO type detector which generates images using list-mode reconstruction algorithm, and 64 slices CT with dose reduction tools such as DoseRight and IDose.

Performance measurements on PET scanner were performed according to the NEMA NU2-2012 standard. Image quality was extended by accounting for different reconstruction parameters (frame timing range from 10 to 1 minute, PSF iteration number 1 to 25, PSF regularization from 2 to 8 mm). A NEMA IEC-61675-1 NU2-2001 body phantom with lesion-to-background ratios 10:1 was used for suitable image reconstruction protocol evaluation, according to EARL guideline procedures.

Performance measurements on CT scanner were performed according to IAEA No.19 (Human Health Series) publication. For different CT exposure parameters check, CTDI measurements in Air, Head

and Body phantoms with 16 cm and 32 cm diameter respectively, using the CT detector of Raysafe Xi were performed. Geometrical efficiency was evaluated by exposure of various beam collimations on Gafchromic XRQA2 radiochromic films. Image quality parameters (MTF, Noise) using all clinical reconstruction filters, resolution modes and noise reduction tool (IDose Index) were obtained by image analysis in commercial available software Radia (Radiological Imaging Technology, Inc) of Catphan® 600 (The Phantom Laboratory, Inc) acquisitions. Influence of DoseRight index parameter change from 30 to 10 on patient dose was studied using anthropomorphic phantom acquisitions.

**Results.** Spatial resolutions ranged from 4.6 mm at 1 cm to 6.0 mm at 20 cm. Sensitivity measured in the centre and at 10 cm were 7.58 and 7.43 cps/kBq, respectively. The measured noise equivalent count rate (NECR) peak was 122.7 kcps at 20.3 kBq/cm<sup>3</sup>. The scatter fraction was 36.6%. Manufacturer's EARL dedicated reconstruction protocol does not perfectly meet accreditation requirements as all others reconstructions with PSF correction. CT acceptance parameters, in most cases, meet manufacturers and international guidelines tolerance specifications. All CTDI<sub>air</sub> and CTDI<sub>vol</sub> obtained values were inside manufacturer's

specification range. Measured difference for geometrical efficiency of 5 mm, 2.5 mm and 1 mm beam collimations was -15.4%, -36.9%, 13.7%, respectively. Decreasing DoseRight index from standard 26 to 24 and 16 dose reductions of 19.8% and 67.3% are observed.

**Conclusion.** Philips Ingenuity TF PET/CT system has overall good performance characteristics, comparable with similar scanners from other manufacturers. The CT part performance meets manufacturer's specifications with some discrepancies, which do not have a significant impact on clinical use. For EARL accreditation programme a better adjustment of reconstruction protocol without PSF algorithm is needed.