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ORIGINAL ARTICLE

Visualization of dose distribution in intraoperative electron beam radiotherapy based on ultrasound images

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Summary

Purpose: *The purpose of this study was to develop a method for dose distribution visualization in the case of Electron Beam Intraoperative Radiotherapy based on the images obtained in the operating room. This cannot be relied on CT images obtained before surgery due to significant tissue deformation.*

Methods: *The ultrasound scanning is the only method to obtain 3-dimensional (3D) reconstruction of a patient's tissue under operating room conditions. We decided to apply this modality as a background to visualize 3D dose distribution in terms of intraoperative radiotherapy (IORT). Dose distribution was obtained on the basis of dosimetric measurements carried out in the water phantom (PDD curves, transversal profiles).*

Results: *The method which has been developed in our department helps optimize the treatment. The amount of information depends strongly on the quality of the ultrasound image. We have verified the method (spatial correctness of dose painting) using commercially available phantom typically used for performance and quality assurance in ultrasound imaging (CIRS) and we noticed good correlation between 3D dose distribution and ultrasound image.*

Conclusions: *Using up-to-date ultrasound tissue images allows better treatment optimization compared to the previous method that uses pre-surgery scans (CT or MRI). It helps optimize the angle of the beam axis and choose the beam with adequate range (energy) and avoid the risk of inaccurate irradiation of the area of interest.*

Key words: *Dose visualization in intraoperative radiotherapy, image-guided treatment planning for IORT, IORT , OAR protecting in IORT, radiotherapy*

Introduction

Intraoperative radiotherapy (IORT) has been developed to deliver a concentrated dose of radiation to a tumor or tumor-bed during surgery. It is believed that direct irradiation of a target performed just after removal of tumor is much more effective in comparison to traditional external boost performed several weeks after surgery [1-6]. In order to determine the treatment time, the anatomy of the tissues to be irradiated must be known. The most important parameter is the actual thickness of the target [3,4,7]. Electron beams (IOeRT-Intraoperative electron beam radiotherapy) and low energy X-rays are usually used for IORT due to their relatively low range. Other types of radiation are characterized by a much greater ability to penetrate matter.

Tissue deformations that occur during surgery indicate that dose calculations should not be performed on the basis of scans obtained before treatment (CT or NMR). Therefore, the irradiation time is usually calculated manually in the operating room as soon as all input data are collected. Physi-

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cists take into account tumor depth, corresponding percentage depth dose (PDD) value and tumor dimensions (field size). The simple assumption is that the density of irradiated tissues does not differ from the density of water, so tissue-heterogeneity correction is not performed. The assumption does not lead to significant errors in typical applications of IORT (eg. breast cancer).

Sparing normal tissues located around the tumor bed can be easily achieved by performing some surgical intervention. Surgeons temporarily remove normal tissue placed above the tumor (closer to the source of radiation than the tumor) from the irradiation field. After radiotherapy the tissue must return to the previous location. If it is necessary, the penetration depth of radiation can also be reduced. One can use boluses, as it is usually done, for example, in external beam radiotherapy. Another solution is to use an aluminum-lead shield that is placed directly behind the target volume [8,9]. Manufacturers offer sets of attenuation plates (boluses) with different thicknesses for each applicator. Discs can be easily mounted on the applicator surface, just above the irradiated tissue (Figure 1). To protect normal tissues located behind the tumor, shielding plates were used (Figure 2).

In our opinion, ultrasound is the only method for obtaining a 3-dimensional (3D) reconstruction of a patient's tissue under operating room conditions. We decided to apply this method in order to visualize 3D dose distribution during intraoperative radiotherapy. When developed, the method would help to optimize treatment and protect tissues located close to the tumor.

Methods

A Mobetron 1000 (IntraOp Medical Corporation, Sunnyvale, CA, USA) accelerator has been used for IeORT in our clinic since 2010 [9]. The device produces three different electron beams with energies of 6MeV,

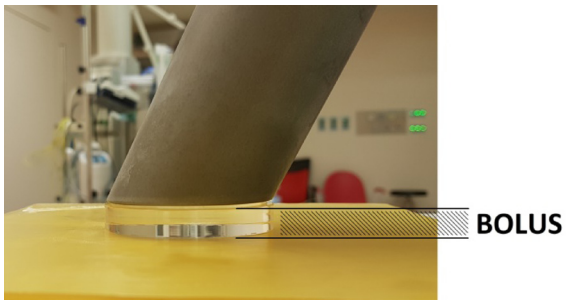

Figure 1. Attenuation plate (bolus) mounted on the surface of the applicator (bevel 30°).

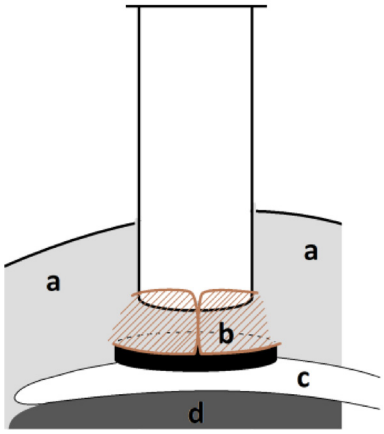

Figure 2. Shielding plate mounted behind irradiated tissue: a - surrounding healthy tissue, b - irradiated tissue, c - protected tissue (rib), d - protected tissue (lungs).

PRESCRIPTION

Aplikator - ϕ	4
Bevel	30
Depth [mm]	20,0
Dose [%]	91,4
method	depth [mm]
Energy	9
Dterap [cGy]	1000
Dref / 500 MU * [cGy]	517,66

CALCULATIONS

OF	1,567
PDG (depth) [%]	91,37
MU	**675**
Dmax [cGy]	**1094,43**

CURRENT OUTPUTS

Dref / 500 MU * [cGy]		
6 MeV	**9 MeV**	**12 MeV**
510,93	517,66	514,05

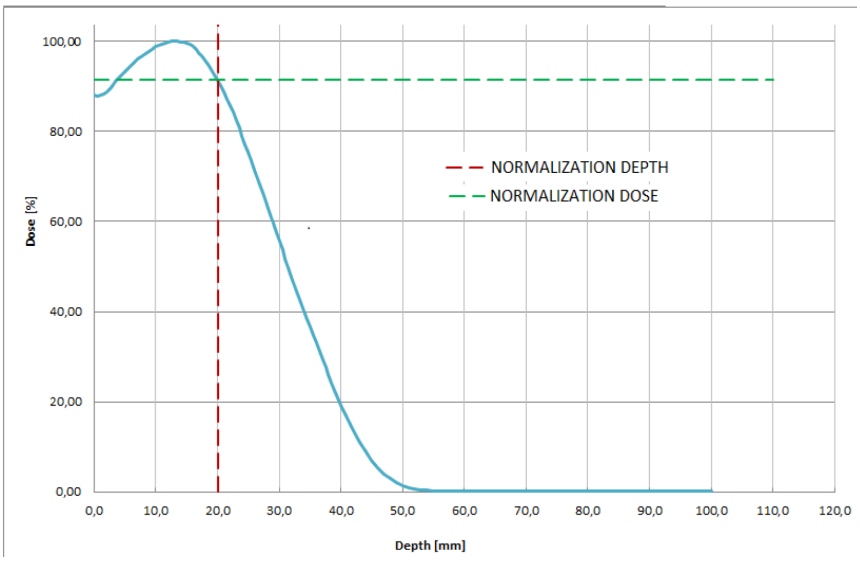

Figure 3. Time calculation form. Left: dose prescription, calculation parameters and actual output; right: dose distribution on the clinical axis.

9MeV and 12MeV. Our accelerator is equipped with round steel applicators with diameters from 3cm up to 10cm (step every 0.5cm). There are three bevels available for each applicator: 0°, 15° and 30°. Thus, the radiation is not always perpendicular to the surface of the tissue. We also use aluminum-lead shields and acrylic boluses with 2 different thicknesses: 0.5cm and 1.0cm.

So far, we have treated over 100 patients. Ninety percent of them had breast cancer, but we also treated patients with prostate, pancreatic and ovarian cancer. We usually used 9MeV beams (60% of cases) and 6MeV beams (38% of cases) more often than 12MeV (only 3 treatments). The thickness of the tissue was measured by two methods: mechanically (using a surgical needle and a ruler) and then with an ultrasound device - Siemens X300. We found that in 60% of cases, the classical measurement differed from the ultrasound measurement by more than 3mm so we had to repeat it.

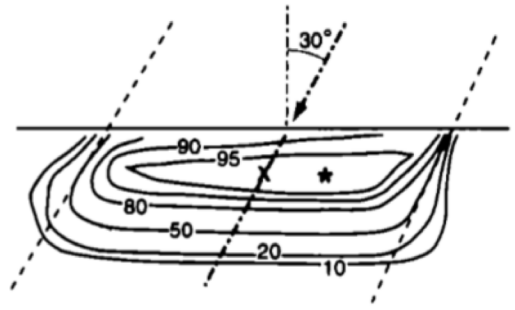

Figure 4. Dose distribution for 9MeV electron beam with oblique incidence 10°. The star indicates the maximum dose [10].

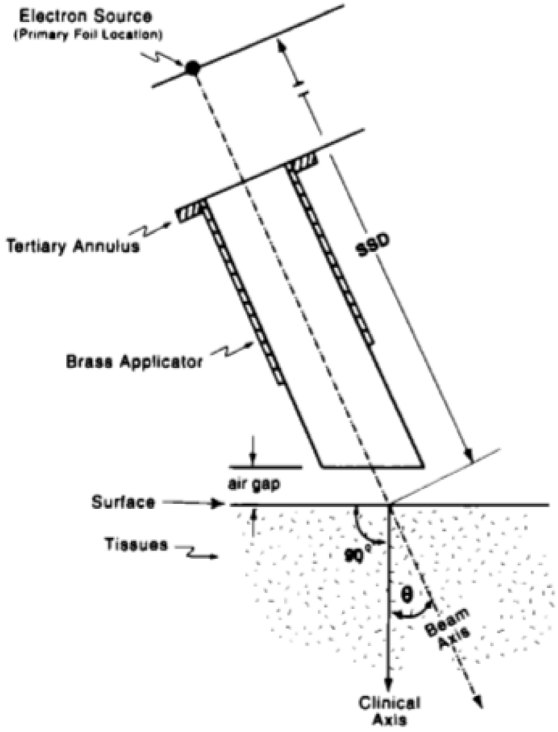

Figure 5. Definition of "clinical axis" for IORT electron application [10].

Treatment time was calculated with the help of a MS Excel spreadsheet. We took into account the radiation field size (applicator diameter adapted to the tumor size) and percentage depth dose value (PDD) corresponding to target thickness. Dosimetry measurements were performed using PTW Freiburg GmbH equipment: MP3 field analyzer with microDiamond detector for PDDs and transversal profiles. PDD curves were acquired for all applicators and for each electron beam produced by the accelerator. Figure 3 presents the calculation form from our spreadsheet.

The dose delivered with a single electron beam is known to be much more homogeneous than the one with a single photon beam. However, it is also more difficult to describe dose distribution in the penumbra area due to strong scattering. The dose gradient on the edge of irradiated volume is not steep, especially when the beam axis is inclined to the surface of the tissue.

It is recommended to use only PDD curves measured perpendicular to the phantom surface while treatment time is calculated. Even when applicators with bevel other than 0° are used, we need to measure the dose distribution along the clinical axis [6,10]. However, in our opinion the calculations of treatment time taking into account only the beam attenuation on the clinical

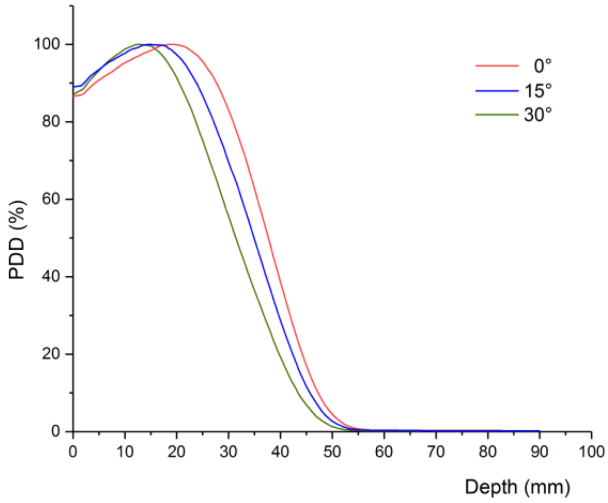

Figure 6. PDD curves measured for 9MeV beam generated by Mobetron 2000.

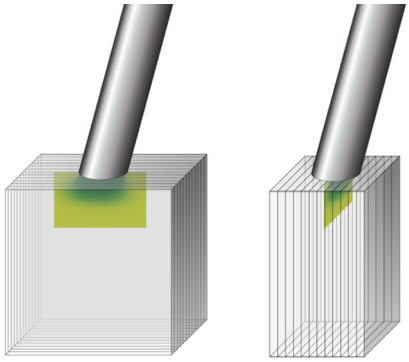

Figure 7. Orientation of the dosimetric film (Gafchromic EBT) in a solid water phantom.

axis (PDD) are insufficient. The use of non-orthogonal beams results in local hot points, consider (as shown in Figure 4, Figure 5 and Figure 6) scattering of particles on the field edge and also endanger the surrounding tissues. We decided to create a technical solution that will show the planned dose distribution against the anatomy of the patient (modified by surgeons).

To present the 3-dimensional (3D) dose distribution, PDDs along the clinical axis as well as beam horizontal profiles are necessary. We suggest to perform PDD measurements for each applicator separately and several profile measurements at different depths (at least every 5mm), in both perpendicular directions - radial and transversal. Alternatively, one can use dosimetric films as shown in Figure 7. The use of dosimetric films eliminates the need for a water phantom and requires much less time than typical measurements. We used self-developing Gafchromic EBT3 films [11-13]. Images recorded on the film were then digitized with an Epson 1000 scanner.

To present the predicted dose distribution (penumbra and practical range of electrons) in a specific clinical situation, we decided to use ultrasound images obtained during surgery. In the past they were typically used only to measure the depth and thickness of the target. We currently use these images as background in order to visualize the calculated dose distribution. Calculations are made with the help of the Matlab software.

To verify the correctness of the calculated dose distribution we used the Octavius 1500 matrix and solid water plates (RW3) from PTW Freiburg GmbH. The matrix was placed horizontally, as presented in Figure 8. We measured the dose distribution in several different planes at depths from 5mm up to 5cm. The distance between planes of measurement was 10mm. We calculated missing values between the planes using simple linear interpolation. The measured 3D dose distribution was then compared with the one predicted by our software.

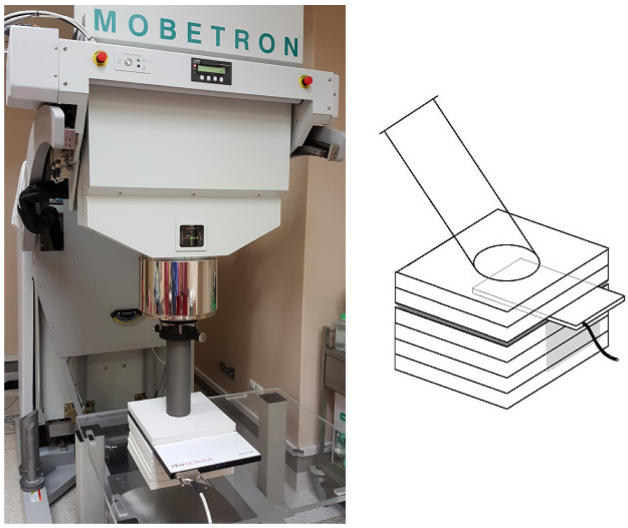

Figure 8. Verification of calculated dose distribution with Octavius 1500 detector matrix.

Results

Figure 9 presents the set of data acquired with the Octavius 1500 for 9MeV electron beam (4cm-

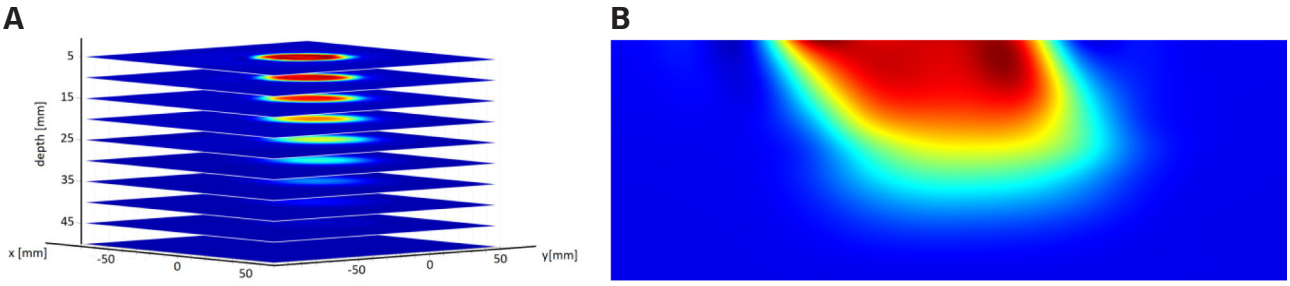

Figure 9. From the set of 2D plane-doses **(A)** to 3-dimensional dose distribution **(B)**.

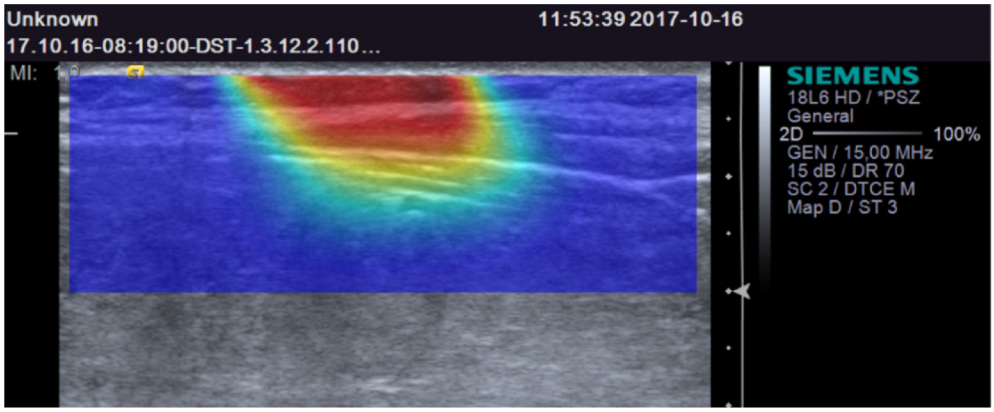

Figure 10. The fusion of 3D dose distribution and ultrasound image.

diameter applicator mounted, bevel 30°) and the final 3D dose reconstruction. We found that the measured dose distribution (PTW Octavius: dose planes) and the predicted one (Matlab calculations based on PDD and transversal profiles) did not differ significantly. The discrepancies were about 2mm in both the transverse direction (penumbra position) and the vertical direction (range of particles). It seems that the results are satisfactory, especially due to the use of the electron beam for IORT.

We attempted to combine the 3D-dose distribution image presented in Figure 9b with ultrasound images taken during surgery. An example of results is presented in Figure 10. The resolution of predicted dose-distribution had to be adjusted to the background image resolution which can be different for each vendor. We had to verify the spatial correctness of dose painting. For this purpose we used scans of CIRS Multi-Tissue Ultrasound Phantom (Model 040GSE). The phantom is typi-

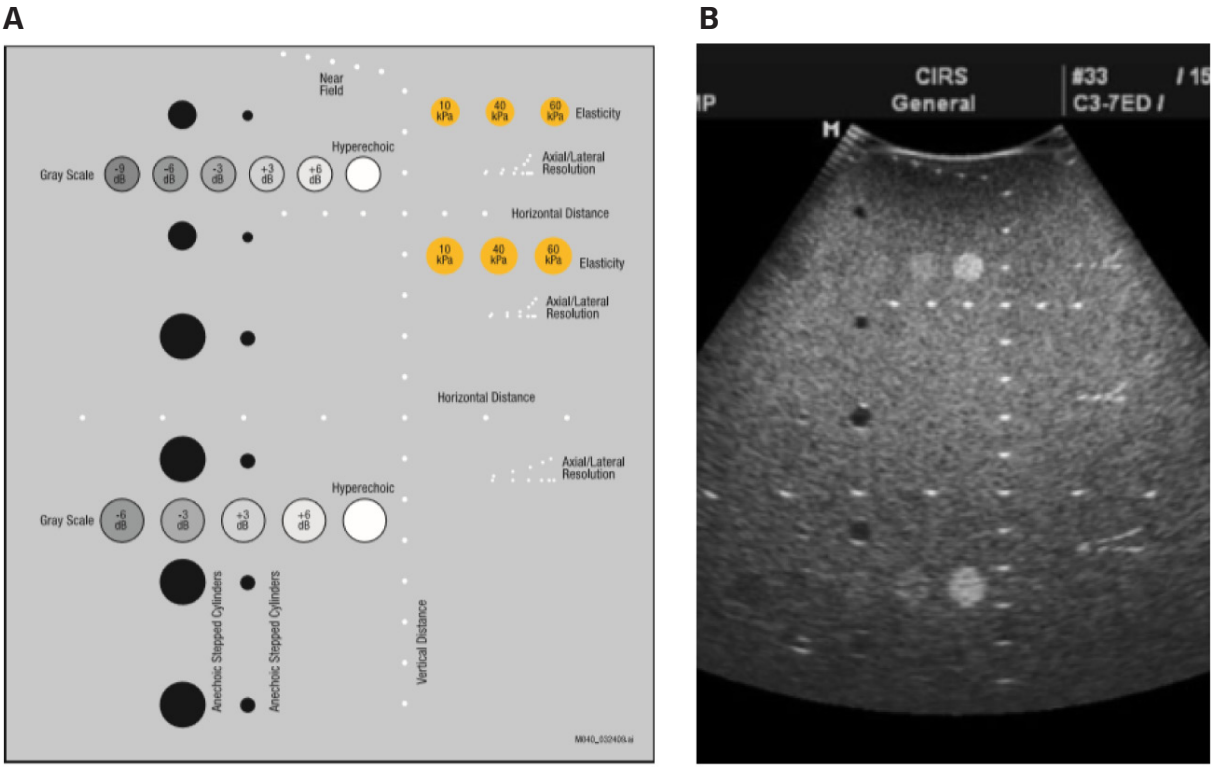

Figure 11. Specification of CIRS 040GSE phantom **(A)**, overall ultrasound image of Model 040GSE **(B)**.

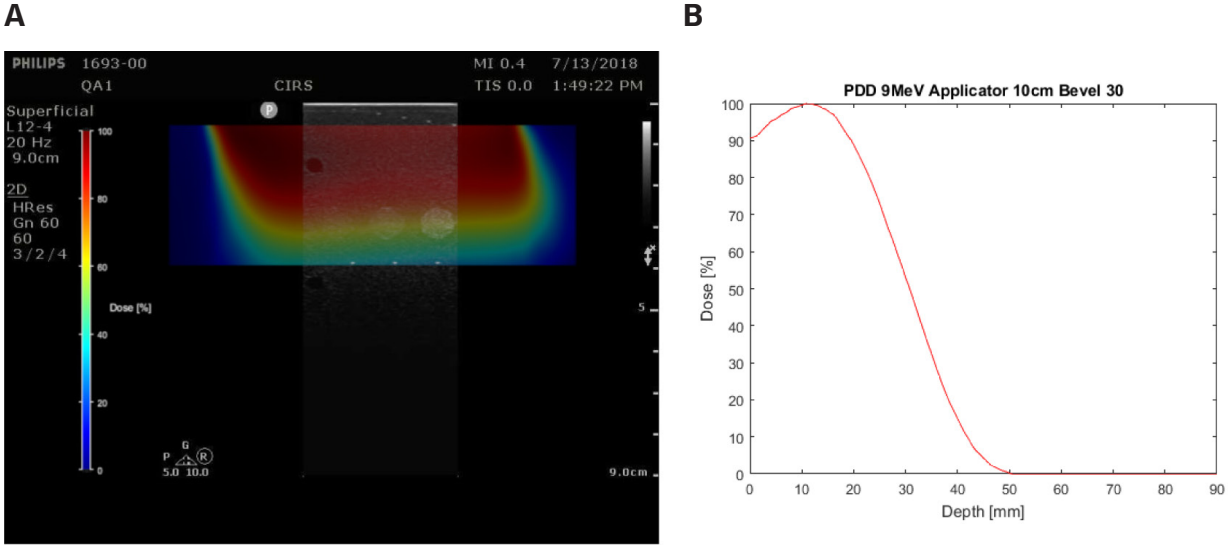

Figure 12. The resultant image obtained as a combination of the dose distribution and ultrasound reconstruction of the CIRS Phantom **(A)** and corresponding PDD curve in the clinical axis **(B)**.

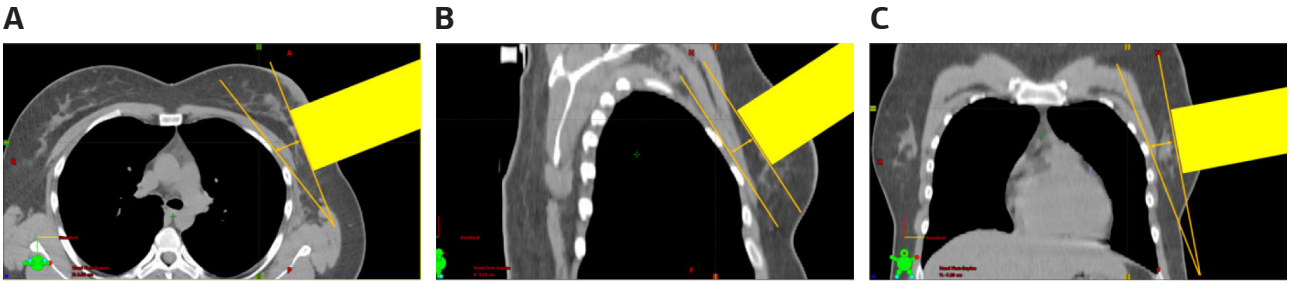

Figure 13. The non-parallel arrangement of the applicator's face to the chest wall shown in the three projections: **A** - transverse, **B** - axial, **C** - sagittal (hypothetical example, visualization obtained with Eclise Treatment Planning System).

cally used for performance and quality assurance in ultrasound imaging.

The phantom contains built-in details with a known position and dimensions (Figure 11). It is easy to see white points (Figure 11a) forming the so-called Vertical Distance Group (VDG) and Horizontal Distance Group (HDG). The vertical group contains 16 points at depths from 1 cm up to 16 cm. The distance between points is exactly 10 mm. There are two groups of points located in horizontal line. The first group contains 6 objects located at a depth of 4 cm and the other one 7 targets at a depth of 9 cm. We used these points to assess the correctness of the dose distribution on the ultrasound image.

As it is shown in Figure 12 at a depth of 4 cm the dose is 20%. Consistently, at a depth of 3 cm - 50%, and at a depth of 2cm - almost 90% of the dose. These estimated values correlate very well (below 2mm) with the PDD curve shown in Figure 12b.

Discussion

The ultrasound imaging is a frequently used tool for visualizing patient anatomy. It is a really fast, low cost, user-friendly and non-invasive method. Surgeons also use it in order to visualize the shape and size of the tissues to be removed.

Measurement of tissue thickness with a surgical needle is characterized by high uncertainty as the measurement only occurs at one point (most often on the central axis of the beam). As the chest wall is not flat, this measurement may not be representative of the entire irradiated area. As presented in Figure 13, the inclination of the applicator's face to the chest wall surface can be visible or not, depending on the type of cross-section. Knowing the shape of the chest wall, one can optimally choose the angle of inclination of the applicator's axis and assess the average thickness of the tissue to be irradiated. This minimizes the risk of inadequate irradiation of tissues located peripherally to the central axis.

As previously mentioned [4,6,10], the calculations of treatment time in a clinical environment are usually performed using a PDD curve, measured along the clinical axis of the beam. Although the presentation of dose distribution over the anatomical structures is not necessary to calculate the treatment time, we believe that it will help to protect the tissues located around the target. The scattering of the radiation at the edge of the therapeutic beam is difficult to describe, especially in the case of non-vertical beams (bevel 15° and bevel 30°) and causes local hot points. Our proposal is one step in improving the quality of intraoperative radiotherapy and needs further investigation.

Conflict of interests

The authors declare no conflict of interests.

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