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Original article

Verification in the water phantom of the irradiation time calculation done by the algorithm used in intraoperative radiotherapy

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A R T I C L E I N F O

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A B S T R A C T

Aim: The investigation of the irradiation time calculation accuracy of the GGPB algorithm used for IORT.
Background: Conventionally, breast conserving therapy consists of breast conserving surgery followed by postoperative whole breast irradiation and boost. The use of intraoperative radiotherapy (IORT) enables the boost to be delivered already during the surgery. In this case, the treatment dose for IORT can be calculated by use of General Gaussian Pencil Beam (GGPB) algorithm, which is implemented in TPS Eclipse.
Materials and methods: PDDs and OFs for electron beams from Mobetron and all available applicators were measured in order to configure the GGPB algorithm. Afterwards, the irradiation times for the prescribed dose of 3 Gy were calculated by means of it. The results of calculations were verified in the water phantom using the Marcus ionization chamber.
Results: The results differed between energies. For 6 MeV the irradiation times calculated by the GGPB algorithm were correct, for the energy of 9 MeV they were too small and for the energy of 4 MeV they were too large for applicators with smaller diameters, while acceptable for the remaining ones.
Conclusion: The GGPB algorithm can be used in intraoperative radiotherapy for energy and applicator sets for which no significant difference between the measured and the prescribed dose was obtained. For the rest of energy-applicator sets the configuration should be verified and possibly repeated.

1. Background

Currently, 60–75% of all breast cancer cases are treated with breast conserving therapy (BCT).[1] The rationale for this therapy is that regardless of the tumor the majority (up to 90%[2]) of the microscopic foci are located only in the vicinity of the initial lesions in the thoracic gland.[2–7] In practice, it is a combination of breast conserving surgery and whole breast irradiation (WBI). The prescribed dose is 50–55 Gy, given in fractions during 5–6 weeks. WBI is often followed by a boost to the tumor bed, which reduces recurrence risk by 40%.[8] In the paper by Sas-Korczynska et al., different techniques of postoperative irradiation within breast conserving therapy

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were described and compared.[9] When intraoperative radiotherapy (IORT) is used, the external boost is replaced by intraoperative boost. That kind of treatment minimizes the geographical error and reduces dose in adjacent tissues, such as the myocardium and the lung.

The modern IORT was initiated in 1965 by M. Abe at Kyoto University, Japan.[10,11] The breakthrough in this method was the development of dedicated mobile linear accelerators such as Mobetron. Mobetrons have been produced since 1990s by IntraOp Medical, Inc.[17] Due to the development of that kind of medical machines, it is possible to apply the whole dose of radiation during the surgery and in the operating room.

The irradiation time in IORT is usually determined manually on the basis of tabulated data which describe dose distribution according to the energy, field size and depth. It is a duty of a medical physicist to find such beam parameters that the dose distribution fits best with the dose prescribed by a radiation oncologist. It is crucial to avoid any failure. Additionally, there is usually more than one possibility of choosing the beam parameters to provide an acceptable solution. Likewise, time needed for this procedure is a relevant factor. Therefore, the automation of irradiation time calculation is essential. Results calculated automatically are more reliable as well as easier and faster to obtain.

One of the possibilities is to use the Generalized Gaussian Pencil Beam (GGPB) algorithm implemented in Treatment Planning System Eclipse by Varian Medical Systems Inc. It calculates the three-dimensional dose distribution of electrons in the irradiated medium and the exposure time in which the medium will receive the prescribed dose.

2. Aim

The aim of this paper was to verify in the water phantom the accuracy of the irradiation time calculation done by the Generalized Gaussian Pencil Beam algorithm used in intraoperative radiotherapy for electrons with energies of 4 MeV, 6 MeV and 9 MeV generated by a dedicated Mobetron, and field sizes with diameters from 3 cm to 10 cm.

3. Materials and methods

3.1. *Generalized Gaussian Pencil Beam algorithm*

The Generalized Gaussian Pencil Beam algorithm, implemented in Treatment Planning System Eclipse by Varian Medical Systems Inc. calculates the three-dimensional dose distribution of electrons in the irradiated medium and the exposure time in which the medium will receive the prescribed dose.[13]

Treatment planning systems calculate the irradiation time for given parameters of the beam and the radiation field to achieve the desired dose in tissue. The TPS Eclipse provides a package of several algorithms which calculate the dose distribution and irradiation time. One of them is the GGPB algorithm which was designed for electron beams. Its three-dimensional dose distribution calculation is based on the Fermi-Eyges electron multiple scattering theory and is the sum of three Gaussian functions. The algorithm calculates the dose for irregular fields with arbitrary orientations and collimator rotation angles. It takes into account inhomogeneity of the medium, the radiation scattered in the air and the contribution from bremsstrahlung. The accuracy of the calculations in a heterogeneous medium is ±5% or ±5 mm.[13]

The GGPB algorithm configuration for IORT requires measuring and introducing to the system the following data for each set of used energy and applicator:

- applicator-specific depth dose curves (PDD),
- output factors (OFs) which are doses measured at the depth of the maximum dose depth normalized to the result for the 10 cm applicator,
- electron mean energy derived from PDD,
- normalization factors which ensure that for the calculated dose distribution the dose at the depth of maximum dose is 100%.[13]

3.2. *Dedicated Mobetron*

Electrons were generated by a Mobetron dedicated to intraoperative radiotherapy, made by IntraOp Medical, Inc. This device accelerates electrons to nominal energies of 4 MeV, 6 MeV, 9 MeV and 12 MeV and emits them with low or high dose rate, 250 MU/min or 1000 MU/min, respectively. Electrons are collimated in an applicator which is placed between the accelerator's treatment head and a patient, 4 cm below the treatment head. There are 15 applicators available with diameters ranging from 3 cm to 10 cm and with the increment of 0.5.[14] Applicators have a triple function. They collimate the radiation, determine the radiation field and keep healthy tissues and skin out of the radiation field.[15]

A Mobetron consists of three parts: treatment module, modulator and operators control console. The control console is used for remote control of the beam during IORT. Programming the console means choosing all parameters of the electron beam: nominal energy, irradiation time and dose rate. In addition, before accepting all parameters and confirming the beam on setup, it is possible to watch the patient on the screen at the console, as the beam eye view color video from the integrated camera is placed in the treatment head. The accelerator can be also operated from the modulator. This option, however, applies only to dosimetry, calibration and measurements made to verify and repair the equipment. It should be pointed out that while operating the radiation from the modulator some parts of the beam automatic corrections are disabled.

3.3. *Verification of the GGPB*

According to the International Atomic Energy Agency TRS 398 report, the dose in water for high energy electron beam with quality Q is obtained by applying the formula (1)

$$D_{w,Q} = M_Q N_{D,W,Q_0} k_{Q,Q_0} \qquad (1)$$

where M_Q is the reading of a dosimeter corrected for the influence quantities such as temperature and pressure, electrometer calibration, polarity effect and ion recombination. N_{D,w,Q_0} is a calibration factor in terms of absorbed dose to water for a dosimeter at a reference beam quality Q_0, k_{Q,Q_0} is a correction factor for the difference between the response of an ionization chamber in the reference beam quality Q_0 used for calibrating the chamber and in the actual user beam quality Q.[16]

All data were collected for energies of 4 MeV, 6 MeV and 9 MeV and 15 applicators with diameters from 3 cm to 10 cm. The measurements order was always the same – from the applicator with the broadest diameter to the applicator with the narrowest diameter.

For each energy-applicator combination three ionization current curves were recorded. On the basis of the analysis made by use of the MEPHYSTO MC^2 software by PTW Freiburg one curve was selected then converted to the PDD and finally converted to the ASCI format which is readable by the GGPB algorithm. The curve selection was necessary because of noisy measurements and some unclear points with lower or higher (even up to 5%) point dose values. There was no difference between proper curves, so any of them could be selected at random. For each PDD, the software calculated the mean energy and the depth of maximum dose. At this depth in the beam axis, the dose for output factors was measured. In this way all data needed for the algorithm configuration were collected and the algorithm could have been configured. Afterwards, irradiation times for a water phantom were calculated by means of this algorithm. The prescribed dose was 3 Gy at the depth of 1 cm for energies of 4 MeV and 6 MeV and 3 cm for energy of 9 MeV. The result of each calculation was the amount of monitor units [MU] which after correction for actual beam efficiency was programmed on the operator control console. The current beam efficiency was established directly before each energy verification measurements. The dose for the calculated irradiation time was measured three times. Finally, the arithmetic mean was compared with the prescribed dose of 3 Gy and the percentage difference was calculated.

3.4. *Measuring setup*

All of the measurements were performed in the water phantom MP1 and MP3 PTW Freiburg. The ionization current curves were recorded by use of the MEPHYSTO MC^2 software which allows registration, presentation and data processing. The dual channel electrometer TANDEM by stem thimble ionization chamber as a reference chamber. The movement of Markus chamber was programmed so that, during the acquisition, it was always moving in the direction of the water surface. For the output factors and verification measurements, the same Markus chamber was used and the UNIDOS dosimeter by PTW Freiburg.

4. Results

PDDs and OFs required for the algorithm configuration were introduced to the GGPB algorithm. The obtained PDDs for the 4 MeV, 6 MeV and 9 MeV electron beams and the 10 cm applicator are depicted in Fig. 1. Fig. 2 shows the output factors for all applicators and energy sets relative to the 10 cm applicator. After completing the algorithm configuration the irradiation times for all sets of energies and applicators were calculated. The results of these calculations are included in Table 1

The results of the calculation verification of the algorithm for beam energies of 4 MeV, 6 MeV and 9 MeV are shown in Tables 2–4 respectively. Each of them contains the results of three dose measurements, their mean and percentage difference between the mean value and the prescribed dose of 3 Gy.

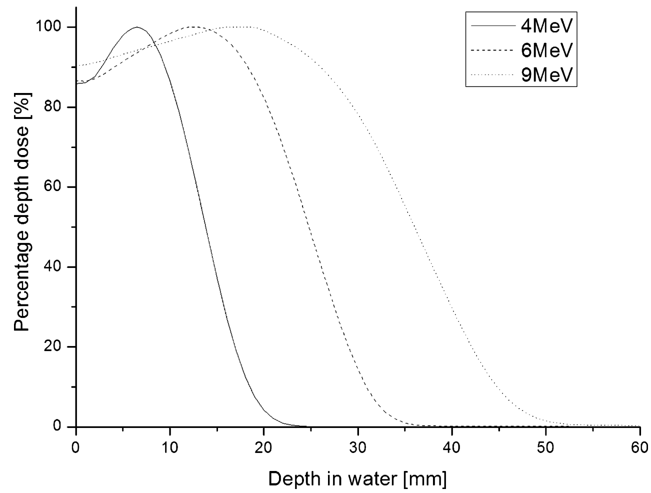

Fig. 1 – Percentage depth of dose curves for 4 MeV, 6 MeV and 9 MeV electron beams and 10 cm diameter applicator.

5. Discussion

The verification of the calculation accuracy of the GGPB algorithm gave different results for different electron energies. It should be pointed out that the lack of stable radiation performance of the accelerator was noted during measurement. This resulted not only in observable variations in beam power, sometimes so large that it was not possible to continue the

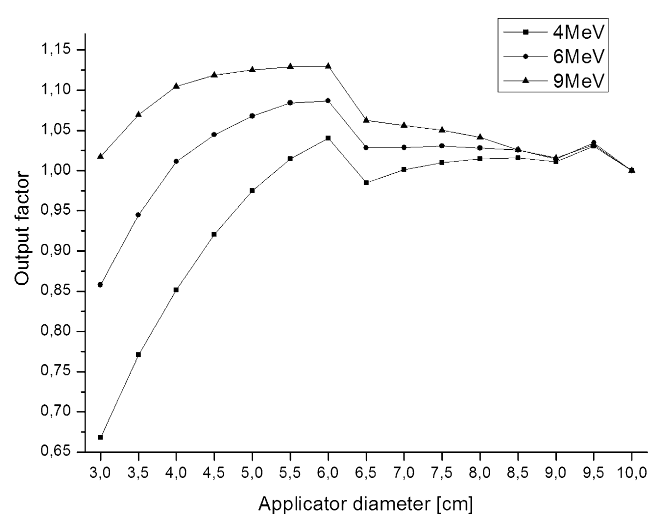

Fig. 2 – Output factors measured at the depth of maximum dose for 4 MeV, 6 MeV and 9 MeV electron beams and applicators from 3 cm to 10 cm diameter.

Table 1 – Irradiation times [MU] for a water phantom calculated by the GGPB algorithm for 4 MeV, 6 MeV and 9 MeV electron beams and applicators from 3 cm to 10 cm diameter. The prescribed dose was 3 Gy at the depth of 1 cm for energies of 4 MeV and 6 MeV and 3 cm for energies of 9 MeV.

Applicator diameter [cm]	Energy [MeV]		
	4	6	9
3.0	584	352	583
3.5	488	319	456
4.0	441	300	392
4.5	403	292	358
5.0	376	286	347
5.5	371	282	330
6.0	352	283	334
6.5	363	297	352
7.0	360	297	357
7.5	357	297	359
8.0	350	299	358
8.5	349	298	377
9.0	352	301	372
9.5	347	292	369
10.0	353	305	381

measurements, but also significant differences between dose values, which were measured one after another. The largest differences were observed for the electron energy of 9 MeV, amounting up to 8% (Table 4). The operation disturbances were clearly visible also during the registration of ionization current curves. Isolated peaks, steps and changes in the level of curves' segments were recorded. In addition, there were a few failures in the system operation manifested by a sudden interruption of radiation. These were related to such interlocks as an invalid profile beam, too high temperature in the therapeutic module or disrupted vacuum in the accelerating section or the magnetron. In the clinical situation radiation is turned on several times for 1–2 min, and then the accelerator remains ready for use for about 2 h until the patient is irradiated, which lasts not more than 2 min. The measurements performed for this paper, on the other hand, lasted usually several hours, so that they must have overloaded the efficiency designed for a clinical use of the accelerator. It may be concluded that the Mobetron was overloaded and therefore did not work steadily enough. During IORT, such disruptions do not occur. The radiation is stable and no significant problems arise in the course of treatment.

Table 2 – Three verification measurements [Gy] for the 4 MeV electron beam, their mean value and the percentage difference between the mean value and the prescribed dose of 3 Gy.

Applicator diameter [cm]	d_1	d_2	d_3	Mean	Difference [%]
3.0	3.323	3.332	3.339	3.331	11.04
3.5	3.257	3.265	3.263	3.262	8.72
4.0	3.283	3.287	3.303	3.291	9.70
4.5	3.255	3.256	3.260	3.257	8.57
5.0	3.205	3.227	3.223	3.218	7.28
5.5	3.283	3.286	3.293	3.287	9.58
6.0	3.192	3.206	3.191	3.196	6.54
6.5	3.109	3.119	3.151	3.126	4.21
7.0	3.154	3.160	3.156	3.157	5.22
7.5	3.132	3.135	3.131	3.133	4.42
8.0	3.093	3.089	3.091	3.091	3.03
8.5	3.098	3.098	3.103	3.100	3.32
9.0	3.100	3.102	3.100	3.101	3.36
9.5	3.081	3.084	3.085	3.083	2.78
10.0	3.064	3.058	3.062	3.061	2.04

Table 3 – Tree verification measurements [Gy] for the 6 MeV electron beam, their mean value and the percentage difference between the mean value and the prescribed dose of 3 Gy.

Applicator diameter [cm]	d_1	d_2	d_3	Mean	Difference [%]
3.0	2.968	2.964	2.966	2.966	−1.13
3.5	2.993	2.997	2.986	2.992	−0.27
4.0	3.001	2.998	3.006	3.002	0.06
4.5	3.023	3.021	3.032	3.025	0.84
5.0	3.020	3.031	3.032	3.028	0.92
5.5	3.038	3.038	3.040	3.039	1.29
6.0	3.136	3.144	3.141	3.140	4.68
6.5	3.038	3.047	3.051	3.045	1.51
7.0	3.063	3.047	3.051	3.054	1.79
7.5	3.065	3.068	3.066	3.066	2.21
8.0	3.073	3.078	3.077	3.076	2.53
8.5	3.056	3.062	3.055	3.058	1.92
9.0	3.059	3.068	3.065	3.064	2.13
9.5	3.038	3.039	3.034	3.037	1.23
10.0	3.068	3.063	3.063	3.065	2.16

Table 4 – Three verification measurements [Gy] for the 9 MeV electron beam, their mean value and the percentage difference between the mean value and the prescribed dose of 3 Gy.

Applicator diameter [cm]	d_1	d_2	d_3	Mean	Difference [%]
3.0	3.220	3.194	3.179	3.198	6.59
3.5	2.954	2.929	3.172	3.018	0.61
4.0	2.800	2.771	3.00	2.857	−4.77
4.5	2.710	2.708	2.744	2.721	−9.31
5.0	2.897	2.724	2.700	2.774	−7.54
5.5	2.634	2.601	2.609	2.615	−12.84
6.0	2.808	2.783	2.637	2.743	−8.58
6.5	2.816	2.642	2.665	2.708	−9.74
7.0	2.704	2.668	2.777	2.716	−9.46
7.5	2.716	2.696	2.696	2.703	−9.91
8.0	2.686	2.686	2.782	2.718	−9.40
8.5	2.825	2.815	2.817	2.819	−6.03
9.0	2.753	2.749	2.756	2.753	−8.24
9.5	2.702	2.712	2.728	2.714	−9.53
10.0	2.883	2.784	2.758	2.808	−6.39

It was assumed that the agreement between prescribed and measured dose is obtained when the percentage difference between them does not exceed 5%. This level of agreement was chosen due to calculation algorithm accuracy. The accuracy of measurements which were done using PTW Freiburg systems such as: water phantoms MP1 and MP3 with automatically controlled chamber position, Markus chamber and Unidos dosimeter with Secondary Standard calibration certificate was not taken into account.

For the 4 MeV beam energy the results of verification were acceptable for measurements which were performed at first (Table 2). Each change of the applicator requires a very small loss in water. In other words, in the course of measurements the water level constantly drops. For lower electron energies, such as 4 MeV, the dose distribution in water depends particularly strongly on the depth, and therefore it can be expected that even a small change in a water level will significantly affect the meter reading. After the measurements for the 4 MeV beam energy, the water level was verified and it was found out that it indeed dropped by 0.6 mm. The changes in the level of water could have been taken into account and corrected. However, it would also imply the need of correcting the distance between applicator and the water surface. At this point it was important that measurement uncertainties due to the continuous matching of the measuring system were not greater than those resulting from the loss of water. Most probably one should rather try to change the applicator in such a way as to minimize the reduction of water volume.

After the measurements also the beam efficiency was again checked. It turned out that it changed, too, increasing by 1.5%. It should be noted that verification of the calculations for the energy of 4 MeV was performed as the first. It was figured out that performance changed because the beam efficiency did not reach a constant value before the beginning of the measurements. Compliance with the higher beam efficiency would result in shorter irradiation time and hence in a lower dose. Thus, it is possible that the inclusion of changes of the beam efficiency and water level would lead to the satisfactory outcome. In the case of the unexpectedly large percentage difference for the 5.5 cm applicator, it was checked that the value of the mean energy for it was lower than for the adjacent applicators. Therefore, it would be advisable to check its PDD.

For the 6 MeV beam energy, the irradiation time was calculated correctly (Table 3). During the measurements, the water level dropped by 0.3 mm and beam efficiency decreased by 0.3%. Nevertheless, it seemed to have no significant influence on the results.

For the 9 MeV beam energy, the irradiation time calculated by the GGPB algorithm was too short for most applicators (Table 4). It was verified that the efficiency of the beam had not changed during the measurements. Due to the fact that serious problems with Mobetron's performance arose during the measurements of PDD for this energy, it would be advisable to re-measure these curves.

The relatively large discrepancy between the prescribed and the measured doses is likely to be the result of algorithm accuracy and some minor problems with instability of the accelerator's performance. While the elimination of the former, although cumbersome and time-consuming, is in a fairly high degree possible, the radiation stability can be hardly moderated. It has to be remembered that all the measurements, calculations and verifications were done in a cubic water phantom. For patients it is a little bit different situation – there are some air gaps and the surface is not so flat as in a phantom. So, basically, there will always be a difference between calculation and dose absorption by irradiated tissues.

6. Conclusions

The results obtained allow to consider the GGPB algorithm as a tool which can be used for intraoperative radiotherapy and not only for conventional radiotherapy. In order to apply it to all energy and applicator sets, the configuration and the verification measurements should be repeated for those sets for which a significant difference between the measured and the prescribed dose was obtained. However, considering that the calculations are made in real-time in a surgeon operating room, when the patient is already lying on the table and waiting for irradiation, it is most important that no mistakes occur when very quick changes of the energy or applicator are made for calculating the best dose distribution. In the next step of the study it is now possible to adjust the algorithm not only for proper beam axis dose and time calculation, but also for dose distribution at the field edges.

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