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Short Communication

Commissioning, dosimetric characterisation and machine performance assessment of the AQURE mobile accelerator for intraoperative radiotherapy

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Abstract

Introduction: The AQURE is a recently designed mobile linear accelerator for intraoperative electron radiotherapy (IOERT). In the study, we assess, report, and compare the dosimetric characteristics obtained during the commissioning of this machine in our Centre.
Material and Methods: The electron energies of the AQURE used in this study are 4, 6, 9 and 12 MeV. The diameters of the cylindrically shaped applicators range from 4 to 10 cm. The measurements were performed (a) by microDiamond detector in a BeamScan water phantom (depth dose distributions, flatness and symmetry of dose profiles, output constancy and linearity) and (b) by Farmer ionisation chamber in a solid water phantom (output related to gantry angle). The results of measurements were compared to analogous results from other IOERT accelerators and were evaluated in the light of scientific recommendations and legal regulations.
Results: The values of the measured parameters fit the recommended ranges. The profiles and the depth dose distributions are close to literature data for other IOERT machines. Any differences between them are caused by the detailed technical solutions which influence the final shape of the obtained dose distributions. The values of mean and most probable energies suggest that the electron beams used during IOERT cannot be considered mono-energetic. We believe that the energy spectrum should be researched and described for each IOERT mobile accelerator before clinical usage.
Conclusion: The measurements confirm the dosimetric accuracy of the AQURE accelerator under the literature guidelines.

Keywords: intraoperative electron radiotherapy; dosimetry; commissioning.

Introduction

Intraoperative electron radiation therapy (IOERT) is a high-dose radiotherapy procedure that is delivered in a single fraction during a neoplastic tumour surgery with direct access to the tumour or tumour bed. The advantages of the IOERT are (a) minimisation of geographic error; (b) the possibility of direct exposure of the tissues to be irradiated; (c) protection of healthy organs by using a limited range of the electron beam; and (d) reducing the risk of complications and improving the cure (so-called local control) of the tumour.[1] Two dedicated IOERT accelerators are available: Mobetron (IntraOP, Sunnyvale, CA, USA) and LIAC HWL (Sordina IORT Technologies, Vicenza, Italy).[2,3] A third accelerator is under development in Poland by researchers from the National Centre for Nuclear Research (NCNR).[4]

The aim of this study was to assess the dosimetric characteristics obtained during the commissioning of the AQURE accelerator (NCNR, Otwock, Poland) in our Centre. The results of measurements were compared to analogous results from other IOERT accelerators and were evaluated in the light of scientific recommendations and legal regulations. To our knowledge, no data concerning the dosimetric properties of this device gathered during commissioning by the third-party users have been published yet.

Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

Materials and Methods

AQURE mobile accelerator

The AQURE is a mobile, intraoperative radiation therapy device that produces electron beams with 4 MeV, 6 MeV, 9 MeV and 12 MeV energies, with a maximum dose rate of 10 Gy/min.[5] The source-to-skin distance (SSD) is 60 cm. The movable base of the accelerator and the possibility of two-plane tilting of its head that is fixed to a rotating crane mounted on a rotating column allow for obtaining a relatively large working space (**Figure 1a**). In addition to the beamforming system that is an integral part of the accelerator head, the electron beams are formed using hard-docked cylindrical applicators with diameters ranging from 4 to 10 cm.[6] The applicators are transparent and constructed from biocompatible material (MED610) with the contact part to the treated area (exit window) perpendicular to the centre of the beam axis (CAX) (**Figure 1b**).[6]

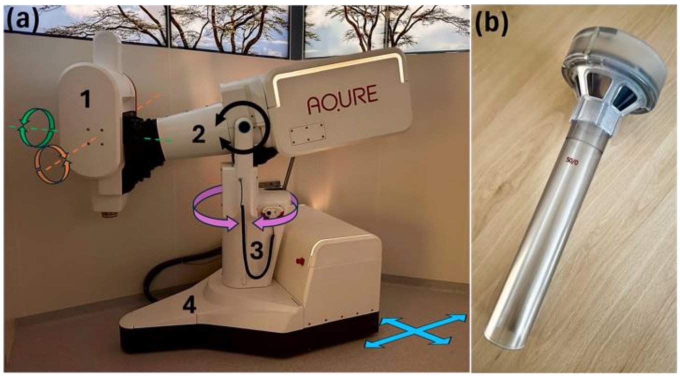

Figure 1. The schematic visualisation of the possible movements of each accelerator part, i.e. 1- head, 2 - crane, 3 - column and 4 - base (a); and an example of the applicator with a diameter of 5 cm (b).

Dosimetric measurements

The measurements were intended to determine the dosimetric parameters of the radiation beam, including:

a) assessment of depth dose characteristics (PDD – percentage depth dose and surface dose),
b) assessment of the flatness and symmetry of the beam,
c) control of the dose monitoring system, i.e. linearity (dependence of dose on the number of monitoring units), repeatability (consistency of short-term performance), the output and its consistency concerning the angular position of the accelerator head.

Most measurements were performed in a BeamScan water phantom (PTW-Freiburg, Germany) using a solid-state synthetic crystal diamond microDiamond detector (PTW-Freiburg, Germany) in the reference positions of the particular parts of the accelerator, i.e. the positions of the column and crane were fixed at 0 deg., and the head was fixed at 0/0 deg. (the notation means the rotational position in x-plane/y-plane, where x-plane is along and y-plane – across the long axis of the accelerator). The exceptions were measurements of the output consistency related to the angular position of the accelerator head, which were performed using the Farmer ionisation chamber (PTW, Freiburg, Germany) placed in the solid PMMA phantom for the reference position of the accelerator (0,0,0/0) and for the extreme positions of the accelerator head that were -45/-58 deg. and 45/35 deg.

The PDDs were collected at a nominal SSD distance (60 cm). The detector was placed parallel to the CAX, and the measurements were performed along the CAX with a 1 mm step starting from the surface of the water and ending at 20 cm depth. Due to measurement geometry that prevents the use of the second (reference) detector during measurements (i.e. the applicator, from one side, was fixed to the gantry and, from the second side, was in direct contact with the surface of the water), the measurements were repeated three times and averaged.[7] The PDDs were analysed with PTW Mephysto software v.3.4 (PTW-Freiburg, Germany). In consequence, the following dosimetric parameters were obtained for every beam configuration:

a) surface dose (D_s),
b) depth for doses: maximum (R_{100}), 90% (R_{90}), 80% (R_{80}), 50% (R_{50}) and 30% (R_{30}),
c) practical range (R_p),
d) the most probable energy ($E_{p,o}$) and the average beam energy ($E_{avg,o}$) on the surface of the irradiated medium,
e) contamination (X_{cont}) (determined only for the reference beam, i.e. formed by an applicator with a 10 cm diameter).

The R means range and is expressed as $R = d * \rho\ [g/cm^2]$, where d is the depth in the medium, in which R was determined and ρ is the density of this medium. Our measurements were in water or solid material with a density like water ($\rho \sim 1\ [g/cm^3]$). Therefore, in the conditions of these measurements, R is equivalent to d and, to simplify, is expressed in millimetres.

The PTW Mephysto software was also used to analyse the profiles and assess the flatness and symmetry of these beams. Beam profiles were measured in cross-plane at the R95 that were determined based on PDDs measurements and were respectively 9.9 mm for 4 MeV beam, 15.8 mm for 6 MeV beam, 23.9 mm for 9 MeV beam and 30.2 mm for 12 MeV beam. Measurements were made with a measuring step of 1 mm over the distance of 16 cm, i.e. from -8 cm to 8 cm relative to the CAX. Like PDD measurements, the detector was placed parallel to the CAX, and the measurements of the profiles were repeated three times and averaged.

The measurements of the dose monitoring system were performed at a measurement point determined based on PDD and located in the CAX at a depth of the maximum dose (R_{100}). Five readings (RDG), one after the other, were gathered to check repeatability. Every has resulted from the emission of 1000 monitor units (MU). We calculated the average RDG (RDG_{AVG}), the standard deviation (RDG_{SD}) and finally, the repeatability defined as $RDG_{SD}/RDG_{AVG}*100\%$.

To check linearity, we used the *RDG* that comes from the emission of 500 MU (RDG_{MU500}), 1000 MU (RDG_{MU1000}) and 5000 MU (RDG_{MU5000}). The RDG_{MU1000} was set as a reference, relative to which the absolute value of the reading deviation was determined for the RDG_{MU500} and RDG_{MU5000}, respectively.

Both checks (repeatability and linearity) were performed for every beam energy and 10 cm applicator by the detector that was oriented parallel to the CAX in the water phantom. The same geometrical conditions were used for the outputs. Nevertheless, the output measurements were performed additionally for every applicator.

The outputs for each energy were defined as the ratio between the *RDG* obtained for the selected applicator ($RDG_{AP,En}$) to the *RDG* obtained when the reference applicator (i.e. with a 10 cm diameter) was used ($RDG_{10,En}$). As previously mentioned, we checked the consistency of the output related to the angular position in the solid phantom. The *RDG* that was gathered for reference position (0/0) was the reading for which the absolute values of the deviation of the *RDGs* gathered for extreme arm position (-45/-58 and 45/35) were determined. For the outputs and their consistency related to the rotational position, every *RDG* resulted from the emission of 1000 MU.

Data assessing

The data obtained during measurements were assessed based on the Polish law directions (RMZ) and the recommendations of the Polish Society of Medical Physics (PSMP), the American Association of Physicists in Medicine (AAPM) and the Italian Centre for Research, Control and Technical Specifications in the health care (ISS).[8-11]

Moreover, based on the literature search, the two most representative studies describing the commissioning process and the dosimetric characterisation of two other IOERT machines were selected.[3,12] In the first one, Winkler et al.[3] show data obtained from the measurements of the 6, 8, 10 and 12 MeV electron beams formed by applicators with diameters ranging from 3 to 10 cm for LIAC HWL. The second paper, published by Wootton et al.[12], presents the dosimetric characteristic of the 6, 9 and 12 MeV electron beams formed by applicators with 4, 7 and 10 cm diameters for the Mobetron 2000 machine.

Choosing an analogous beam configuration, we compared our data obtained for the 6 and 12 MeV beams formed via a 6 cm applicator with the data from LIAC HWL and the data from 6, 9 and 12 MeV beams formed via a 10 cm applicator with the data from Mobetron.

Results

Figure 2 shows the outputs for electron beams with nominal energies of 4, 6, 9 and 12 MeV, formed using cylindrical applicators with diameters of 4, 5, 6 and 10 cm available on the AQURE mobile accelerator for IOERT. In **Figures 3** and **4**, we show examples of the PDD distributions for the 4, 6, 9 and 12 MeV beams formed by the 5 cm applicator and the profile functions for 4 MeV beams formed by the applicators with diameters of 4, 5, 6 and 10 cm.

In all figures showing the relationship between the nominal energy, the diameter of the applicator and the analysed parameter or dosimetric distribution, a unified graphic identification was used, meaning: (1) colours - nominal energies, i.e. red - 12 MeV, orange - 9 MeV, yellow - 6 MeV, green - 4 MeV and (2) shape of the points - diameter of the applicators, i.e. circle (○) - 10 cm, rhombus (◇) – 6 cm, triangle (△) – 5 cm and square (□) – 4 cm.

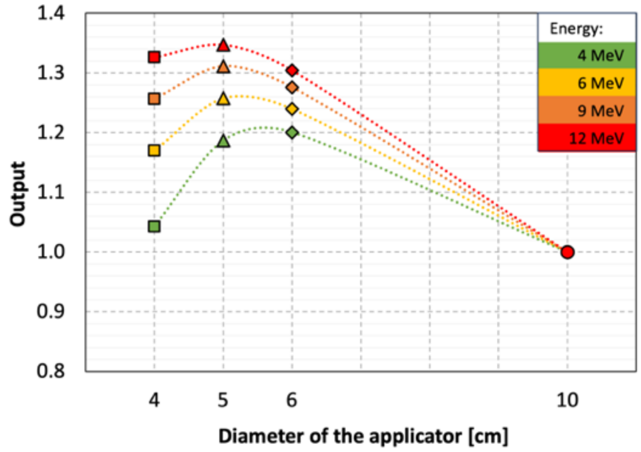

Figure 2. The outputs for electron beams with nominal energies of 4, 6, 9 and 12 MeV, formed using applicators with diameters of 4, 5, 6 and 10 cm.

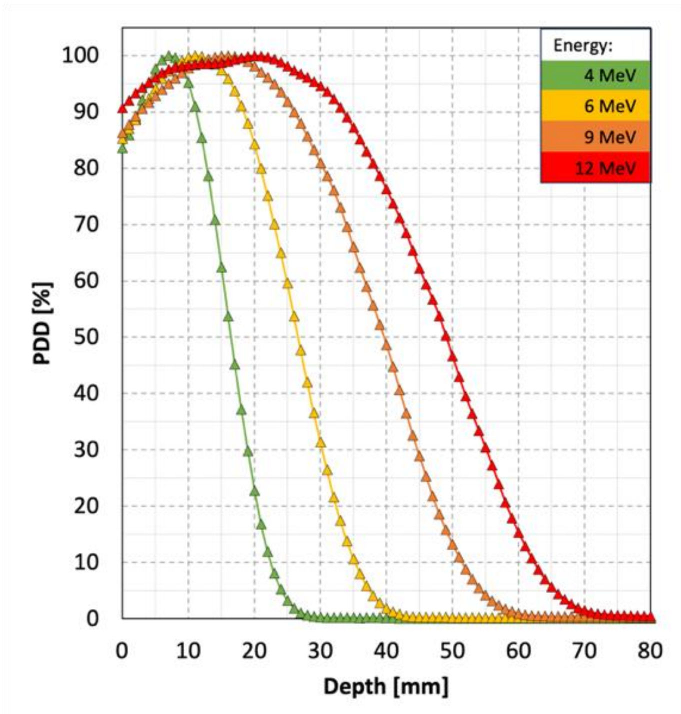

Figure 3. The percentage depth doses (PDD) for electron beams with nominal energies of 4, 6, 9 and 12 MeV, formed using applicators with a diameter of 5 cm.

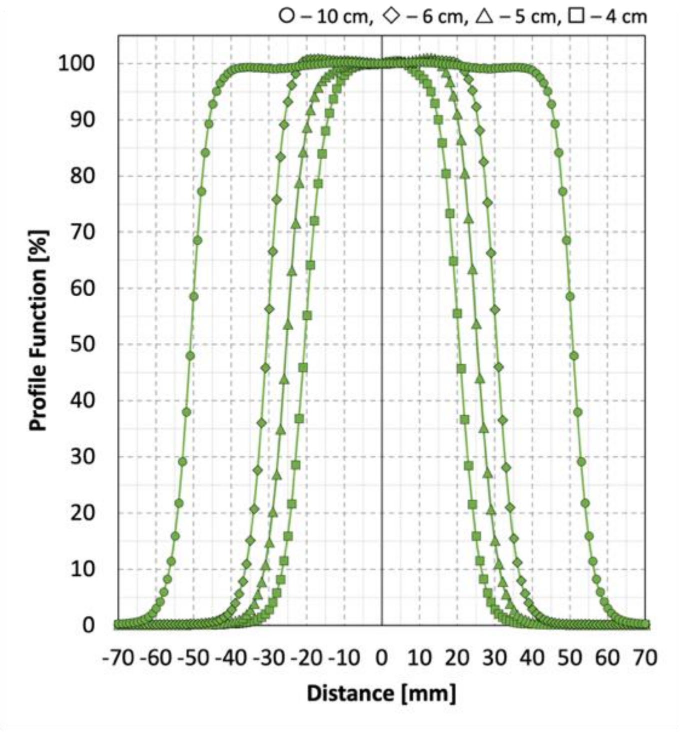

Figure 4. The profile function for electron beams with a nominal energy of 4 MeV, formed using applicators with diameters of 4, 5, 6 and 10 cm.

Assessing the dosimetric parameters obtained during the measurements, we noted that all were acceptable according to Polish law and the literature recommendations (**Table 1**).

Tables 2 and **3** show the comparison of the dosimetry data obtained for the AQURE machine, the LIAC HWL, and the Mobetron 2000. The data in the tables are limited by the range of the data presented in the referenced studies on LIAC HWL and Mobetron 2000.

Discussion and Conclusions

The measurements confirm the dosimetric accuracy of the AQURE accelerator under the literature guidelines.

The profiles and the depth dose distributions are close to literature data for other IOERT machines. Any differences between them are caused by the detailed technical solutions which influence the final shape of the obtained dose distributions. The values of mean and most probably energies suggest that the electron beams used during IOERT cannot be considered monoenergetic. We believe that the energy spectrum should be researched and described for each IOERT mobile accelerator before clinical usage. There are three main types of methods for determining the energy spectrum of the electron beam produced by an accelerator. The first is based on direct spectroscopic measurement in which the energy of individual electrons in a beam is measured using, for example, a scintillation detector.[13] The second method is based on measuring energy with a magnetic spectrometer.[14]

Table 1. The comparison of the worst value of dosimetric parameters obtained during our measurements (Worst OBS) with the limit values of acceptable discrepancy according to AAPM[10], ISS[11], PSMP[9] and RMZ[8].

Parameter	The value [%]:				Selected as limit	Worst OBS
	AAPM	ISS	PSMP	RMZ		
Repeatability	≤ 2	≤ 1	≤ 0.5	≤ 0.5	≤ 0.5	0.3
Linearity	≤ 1	≤ 2	≤ 2	≤ 1	≤ 1	0.7
Output vs gantry angle	ND	ND	≤ 2	≤ 2	≤ 2	1.0
Symmetry	≤ 3	≤ 3	≤ 3	≤ 3	≤ 3	2.2
Flatness	≤ 3[@]	≤ 5	≤10[#]	≤ 5	≤ 5	4.2

@ i # - the methodology for determining flatness is different from that adopted in the RMZ

Table 2. The comparison of the dosimetric parameters for the AQURE and the LIAC HWL[3] accelerators. The list concerns electron beams with nominal energies (EN) of 6 MeV and 12 MeV, formed with an applicator with a diameter of 6 cm.

Accelerator	AQURE	LIAC HWL	AQURE	LIAC HWL
EN [MeV]	6		12	
D_s @ 1mm [%]	85.9	87.7	93.3	91.8
R_{100} [mm]	11.5	10.5	17.5	17.0
R_{90} [mm]	17.6	16.4	33.8	30.6
R_{50} [mm]	26.5	24.0	49.4	44.5
R_p [mm]	35.2	32.0	63.9	58.2
$E_{p,0}$ [MeV]	7.2	6.6	13.0	13.0
$E_{avg,0}$ [MeV]	6.2	5.6	11.5	10.4
Flatness [%]	1.3	2.6	1.4	1.4
Symmetry [%]	1.2	1.6	1.0	0.9

Table 3. The comparison of the dosimetric parameters for the AQURE and the Mobetron 2000 (MBT)[12] accelerators. The list concerns electron beams with nominal energies (EN) of 6, 9 and 12 MeV, formed with an applicator with a diameter of 10 cm.

Accelerator	AQURE	MBT	AQURE	MBT	AQURE	MBT
EN [MeV]	6		9		12	
D_s [%]	89.0	86.0	92.3	90.0	94.2	94.0
R_{100} [mm]	10.5	11.5	15.0	18.5	17.5	19.3
R_{90} [mm]	17.6	17.3	26.3	28.1	33.8	38.8
R_{80} [mm]	20.5	19.6	31.0	31.3	39.5	43.7
R_p [mm]	35.7	30.8	53.3	47.4	64.9	64.0
$E_{p,0}$ [MeV]	7.3	6.3	10.8	9.7	13.2	13.0
$E_{avg,0}$ [MeV]	6.2	5.6	9.3	8.8	11.8	12.1

Both approaches are very difficult to implement in clinical conditions because they require very specialised equipment and interference in the structure of the accelerator head in order to gain access to the output window of the acceleration section. The third group are methods of backward reconstruction of the spectrum based on the measured PDD thanks to the use of appropriate mathematical techniques.

Parallel to the presented study, we established our customised methodology for the backward reconstruction that will be a basis for further research on the energy spectra of the beams generated by the AQURE accelerator.[15]

Editor's comment

The abstract of the work was submitted to the 18th Congress of the Polish Society of Medical Physics (held in Poznań, Poland, 19-21 September 2024). The authors of the work were invited by the Scientific Committee of the Congress and the Editor-in-Chief of the Polish Journal of Medical Physics and Engineering to present their work in the form of a Short Communication in the Journal.

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