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The Dosimetry Characteristics of a Low Energy Photon Intra-Operative Radiotherapy System

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Abstract

Objective

To commission a low energy photon intra-operative radiotherapy (IORT) system and analyze the dosimetric characteristics of the X-ray probe, spherical, flat and needle applicators of different sizes.

Methods

A dedicated water phantom, a parallel-plate ionization chamber and an electrometer are used to measure the dosimetric performance of X-ray probe within different tube voltage/tube current and the depth dose rate, isotropy, dosimetry reproducibility of X-ray probe and 3 different applicators of different sizes; then the measurements are used to compare with system data.

Results

The difference in depth dose rate between the measurements and system data for 40 kV/40 μA and 50 kV/40 μA X-ray source are -1.56% ± 1.29% and -2.16% ± 1.36%, respectively. The deviation in depth dose rate between the measurements and system data for 50 kV X-ray probe with different tube current is ±2.0%. The difference in depth dose rate between the measurement and system data is -10.0% ~ 2.3% for the whole set of spherical applicators. The deviation of transfer coefficient between measurements and system data is from -8.9% to 4.2% for all spherical applicators of different sizes, -1.98% ~ 6.34% for flat applicators, and -6.17% ~ 0.75% for needle applicator, respectively. The range and changed trend of transfer coefficient are different between applicators. The dose gradient varies significantly for different applicators of different sizes; higher surface dose rate with steeper gradient depth dose are observed in smaller applicators; the transfer coefficient changed with the applicator of type and diameter and depth of measurement.

Conclusions

The dosimetry performance of the low energy X-ray IORT system changes greatly with the type and diameter of the applica-

tors and depth of measurement, which should be taken into account in the clinical application.

Keywords: Intra-operative radiotherapy; Low energy photon; Dosimetry characteristics; Applicators

Abbreviations

IORT: Intra-Operative Radiotherapy;

XRS: X-ray source;

IC: Ionization chamber

Introduction

Intra-operative radiotherapy (IORT) with high energy electron beam or low energy photon beam possesses advantage of delivering a single high dose radiation directly to the tumor bed during the surgical procedure and preserving the deep normal tissues. With the introduction of light-weighted and easy-to-move device which includes Mobetron® MeV electron beam system [1] (IntraOp Medical Corporation, California, USA), NOVAC™ 7 electron beam system [2] (New Radiant Technology SpA, Italy) and the INTRABEAM® 50 kV X-ray system [3] (Carl Zeiss Medical Company, Germany), IORT technique is applied more frequently in the cancer treatment [4].

The INTRABEAM, a low energy X-ray IORT system is equipped with the spherical, flat and needle applicators applied in the treatment of malignant neoplasms in different parts of the body. The spherical applicators are mainly used for the IORT of early breast cancer after conserving surgery [5,6]; while the flat applicators for the irradiation of flat lesion of small area due to its limited size [7], and the needle applicators for the treatment of vertebral metastasis together with vertebral plasty (Kyphoplasty) [8]. Very few tests on the dosimetry characteristics of the low energy IORT system especially for the flat and needle applicators have been reported. There still remains controversial for the dosimetric characteristics and clinical application of IORT.

Our previous study had investigated the property of the bare probe and dosimetric characteristics for the spherical applicators[9]. In this paper we further introduce the dosimetry characteristics of the low energy photon (IORT) system under optional tube voltages/tube currents, and the depth dose rate, the isotropy and the measurement repeatability for the spherical, flat and needle applicators. The purpose of the study is to investigate the dosimetric performance of the system and verify its reliability, and finally explore its potential and limitation in clinic application.

Method and Materials

Introduction of the system

The micro x-ray source (XRS) of the INTRABEAM system with a weight of only 1.5 kg is fixed into the six-degree freedom floor stand during clinical application. It can be locked and placed into the operation cavity from different angles within a large scope of movement. The principle of XRS is similar to diagnostic X-ray machine with electrons emitting cathode gun. After accelerated by high voltage electric field, the electrons are drifted into a 100 mm long hollow probe with diameter of 3.2 mm to the gold target under the guidance of bending magnet to deliver X-ray with a spectrum of 0-50 kV. A spherical dose distribution is generated in a deflection scanning way by bombard between the electrons and gold target. Figure 1a depicts the overview of the XRS. The system provides two modes (40 kV and 50 kV) accelerating voltage. The 40 kV mode provides a single tube current of 40 μA, whereas the 50 kV mode provides 5, 10, 20 and 40 μA tube current. 50 kV/40 μA X-ray is recommended in order to reduce treatment time.

Figure 1b-d depicts outlook of spherical, needle and flat applicators. Spherical applicators with diameter ranging from 1.5 cm to 5.0 cm consist of solid homogeneous polyetherimide, which can be divided into two groups according to the structure mounted interiorly; the interior wall of the probe is embedded with a thin metal sheath for the applicators of diameter ≤ 3 cm whereas no metal sheath for those of diameter > 3 cm[10]. Flat applicators with diameter ranging from 1.0 cm to 6.0 cm with 1.0 cm increment and length of the applicator increases with the diameter increasing. The flat applicator presents with a hollow cylinder structure which can shield low energy X-ray effectively. Homogeneous dose distribution is formed with attenuation by the conical flatting filter at the bottom of the applicators[7]. The needle applicator is designed as a hollow probe with the inner diameter slightly larger than the XRS probe and the outer diameter of 4.4 mm.

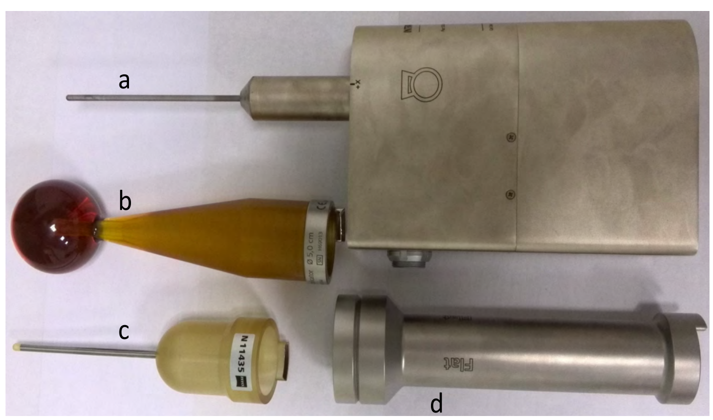
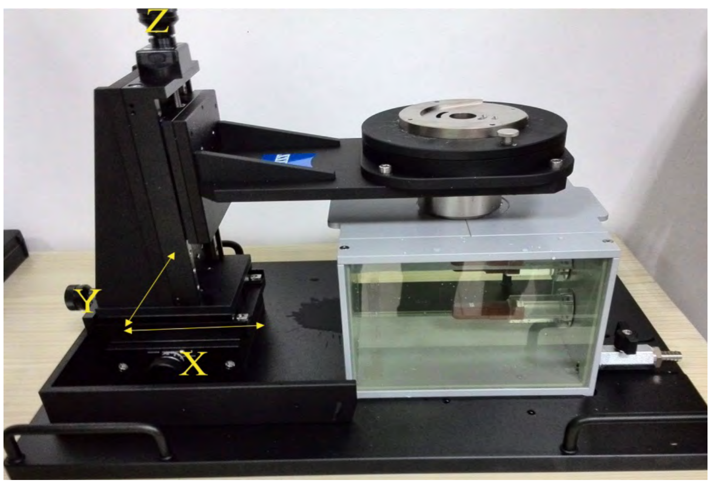


Figure 1. The XRS and applicators of 3 different shapes.(a) the XRS, (b) the spherical applicator, (c)the Needle applicator, (d) the flat applicator.

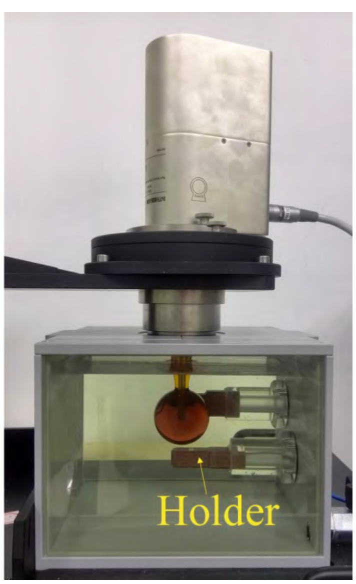
Dosimetry measurement and analysis

The device for measurement includes a dedicated water phantom with radiation protection design (Carl Zeiss Surgical GmbH), a parallel plate ionization chamber (volume of 0.0053 cm^3, type 34013, PTW, Freiburg, Germany) and a dosimeter (UNIDOS E, PTW, Freiburg, Germany). The platform of water phantom can be adjusted vertically (by rotating the knob Z , as shown in Figure 2a) with range of 10.0 cm and precision of 0.001 mm, while the adjustable range in the X/Y plane (as shown in Figure 2a) for the right measurement position that faced to the XRS probe is relatively small. The platform is designed as a turnable structure with 8 positions representing the isotropic direction in the X/Y plane for measuring the isotropy of the dose distribution.

Figure 2. (a) The illustration for the definition of the X/Y plane with double-headed arrows and the X,Y,Z coordinates labeled at reference rotary knobs. (b) Setup of the measurement platform with a spherical applicator inserting into the water phantom.



(a)



(b)

Two waterproof measuring chambers in the water phantom are designed to measure depth dose rate and isotropy respectively. The ionization chamber(IC) is inserted with the holder into the measuring chamber (as shown in Figure 2b), which is closed with special cover during measurement. The depth dose rates are measured for bare probe under conditions of different tube voltage with the constant tube current of 40 μA and different tube current with constant tube voltage of 50 kV. The depth dose rates, the isotropic dose distribution in X/Y plane (flat applicator excluded) and the repeatability are measured for 3 types applicators of different sizes. The lowest surface of the probe was defined as the isocenter of 0 mm in depth. Due to the certain thickness of the holder wall and the air gap between the holder and IC, the measurement in Z direction ranges from 2.0 mm to 44.0 mm with 0.5 mm increment when the distance is less than 40.0 mm, whereas 1.0 mm for 40.0 mm or deeper. One minute was taken for the collection of electric charge read in the UNIDOS E for calculation.

The depth dose rate D_w at reference depth (r) are calculated by the equation (associated protocol: IAEA TRS277)(1):

$$D_{DW}(r)[Gy/min] = N_k[Gy/C] \times Q(r)[C] \times T[K]/T_0[K] \times P_0[hPa]/P[hPa] \times k_Q \times k_{Ak} \times 1[1/min] \quad (1)$$

N_k = detector calibration factor (see the certificate, the number is 4247000000)

Q(r) = measured charge Q in one minute

T = current temperature

T_0 = reference temperature (see calibration certificate of ionization chamber)

P_0 = reference air pressure (see calibration certificate of ionization chamber)

P = current air pressure

k_Q = beam quality correction factor (see PTW certificate, the quality level of XRS is approximately T30, known as beam qualities according to the Geman national standard DIN 6809-4)

$k_{Ak\rightarrow DW}$ = air kerma→ absorbed dose to water conversion (correction factor for PTW type 34013 IC, the number for T30 is 1.054)

The transfer coefficient $TF_z(r)^{appl}$ for different applicators at reference depth (r) is calculated by the equation (2):

$$(TF_z(r))^{appl} = (D_w(r))^{appl} / (D_w(r))^{xrs} \quad (2)$$

$(D_w(r))^{appl}$ = calculated dose rate at reference depth (r) according to equation (1)

$(D_w(r))^{xrs}$ = calculated dose rate at the same position of Z direction without the spherical applicator

The percentage error E at reference depth (r) is defined by the equation (3):

$$E(r) = \left(\left(D_w(r)^{measurement} - D_w(r)^{software} \right) / D_w(r)^{measurement} \right) \times 100\% \quad (3)$$

$D_w(r)^{measurement}$ = dose rate at reference (r) calculated by equation (1) according to charge Q read in the dosimeter.

$D_w(r)^{software}$ = dose rate at reference (r) acquired from user manual or software profile in the control system.

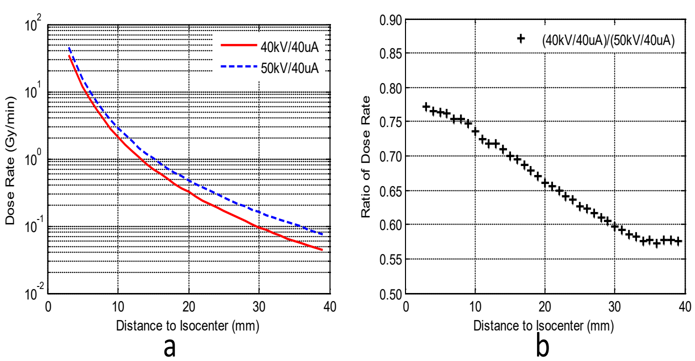
Matlab (MathWorks, USA) software is used for data analyzing, fitting and plotting.

Results

Depth dose rate of bare probe under optional tube voltages with constant tube current

Figure 3 depicts the depth dose rates with constant tube current of 40 μA under the tube voltage of 40 kV and 50 kV. The red line represents the average of 3 measurement values under 40 kV/40 μA, the blue line for the average of 3 measurement values under 50 kV/40 μA. The measurement values are smaller than system data with a small deviation. The average deviation between the measured value and the system value is -1.56% ± 1.29% (range: -3.68% ~ 1.92%) for tube voltages of 40 kV and -2.16% ± 1.36% (range: -3.65% ~ 2.83%) for 50 kV, respectively. The ratio of depth dose rates between 40 kV/40 μA and 50 kV/40 μA ranges from 0.57 to 0.77, which is >0.7 when the depth of measurement is within 10 mm.

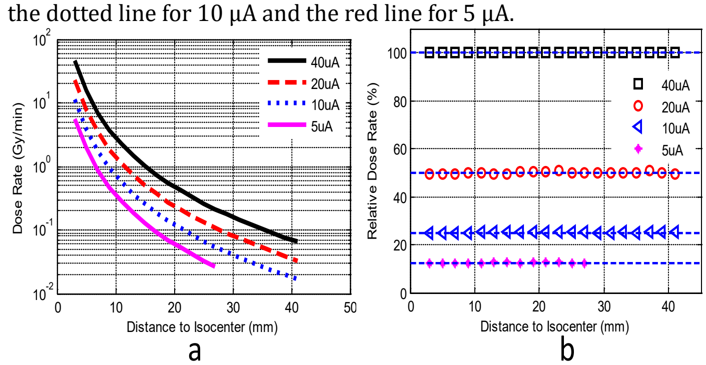
Figure 3. The curves for depth dose rate under optional tube voltages with constant tube current (40 μA).(a)The red line is for the average values of depth dose rate for 3 measurements under 40 kV/40 μA, the blue line for the average values of depth dose rate for 3 measurements under 50 kV/40 μA; (b)the black "+" symbol is for the ratio of average values of depth dose rate under 40 kV/40 μA to that under 50 kV/40 μA.



Depth dose rate of bare probe under optional tube currents with constant tube voltage

Figure 4a shows the depth dose rates of bare probe with constant tube voltage of 50 kV under a serial of tube currents 40 μA, 20 μA, 10 μA and 5 μA. The measurements at tube voltage of 5 μA are made from 2 mm to 27 mm due to rapid fall of electric current beneath 27 mm. The dose rate values at the same depth fall as the tube currents decrease.

Figure 4. The curves for depth dose rate (a) and normalization (b) under optional tube currents with constant tube voltage (50 kV). The black line is for the tube current of 40 μA, the dashed line for 20 μA, the dotted line for 10 μA and the red line for 5 μA.



For the constant tube voltage, the relationship between the depth dose rate and tube current is in proportion of tube current applied. As shown in Figure 4b, the system theoretical dose rate for 20 μA, 10 μA and 5 μA is 50%, 25% and 12.5%, respectively when it is normalized to that under 40 μA. Deviation between the measured value and the system theoretical data for different tube current are in the range of -1.45% ~ 1.72% for 20 μA, -1.22% ~ 1.66% for 10 μA and -2.30% ~ 0.80% for 5 μA, respectively.

Depth dose rate of the optional applicators

The depth dose rate were measured for spherical, flat and needle applicators under the condition of 50 kV/40 μA. Figure 5 depicts the calculated absolute depth dose rates for those 3 applicators of different diameters as a function of the distance from the IC effective measurement point to the surface of the applicators. The data of depth <2 mm is acquired by the fitting function plotted by measurement values. The average difference in depth dose rate between the measurement and system data for spherical applicators is -5.1% ~ -0.1% (range: -10.0% ~ 2.3%). As shown in Figure 5a, the absolute dose rate decreases with the increment of the depth, and the depth dose gradient of different applicators is different. The range of surface dose rates for the spherical and flat applicators is 0.48 ~ 3.58 Gy/min and 0.37 ~ 9.93 Gy/min, respectively. Our data show that the applicator with smaller diameter presents with higher surface dose and larger dose gradient. There is curve overlapping for spherical applicators in diameter of 2.5 and 3.5

cm, 3.0 and 4.0 cm due to the different probe channel design for diameter of ≤3 cm group and>3 cm group. The difference in depth dose rate for flat applicators in different diameters decreases with increase of diameter . Figure 5c shows that the depth dose rate drops rapidly in the vicinity of the surface area for the needle applicator of 4.4 mm in diameter.

Figure 5. The curves for absolute depth dose rate for different applicators as a function of the distance to the surface of applicators. (a) the absolute depth rate for spherical applicators ;(b) the absolute depth rate for flat applicators;(c) the absolute depth rate for needle applicator.

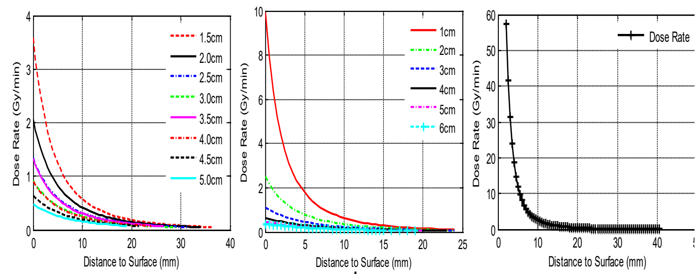


Figure 6 shows the percentage of depth dose in which the depth dose rates are normalized to the value at 0 mm depth for all spherical and flat applicators and normalized at 2 mm depth for the needle applicator. The percentage of depth dose varies significantly as the measurement depth and applicator size changes. It drops to approximately 50% at 3 mm from the surface for spherical applicator of 1.5 cm diameter and at 5 mm for spherical applicator of 5.0 cm diameter, at 1 mm from the surface for flat applicator of 1.0 cm diameter and at 5 mm for flat applicator of 6.0 cm, and at 3 mm for needle applicator.

Figure 6. The curves for normalization of depth dose rate for different types of applicators as a function of the distance to the surface of applicators. (a) the normalization of depth rate for spherical applicators;(b) the normalization of depth rate for flat applicators;(c) the normalization of depth rate for needle applicator.

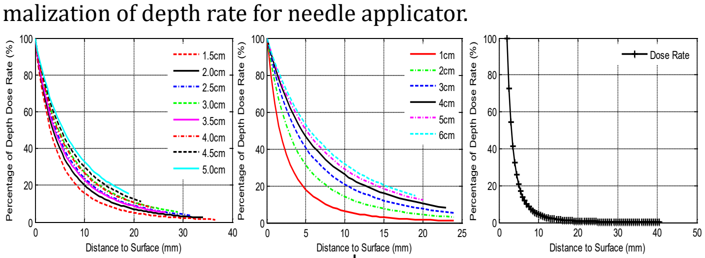
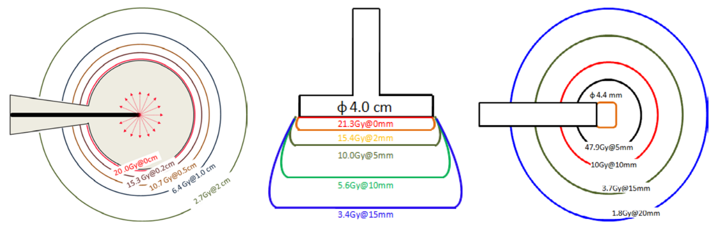


Figure 7 shows schematic diagram of radiation dose distribution for the representative spherical, flat and needle applicators according to the measured values of the center axis. The prescribed radiation dose is 20.0 Gy at the surface for spherical applicator in diameter of 4.5 cm, while 10.0 Gy at depth of 5.0 mm for flat applicator and 10.0Gy at depth of 10.0 mm for needle applicator.

Figure 7. Representative dose distribution for different types of applicators according to the measured values of the center axis and isotropy of spherical applicators. (a) spherical applicator of ϕ4.5 cm;(b) flat applicator of ϕ4.5 cm;(c) needle applicator of ϕ4.4 mm.



The dose rate at certain depth varies with the type and size of applicators when 10.0 Gy is prescribed at 5.0 mm from the surface of the applicator. As shown in Table 1, the dose distribution is different for different applicator. For specific type of applicator, the higher surface dose with deeper dose fall off is observed in smaller applicator. For same size of applicator, the higher surface dose with larger dose gradient is observed in flat applicator than in spherical one. The needle applicator presents highest surface dose and largest dose gradient.

Transfer coefficient

As shown in equation (2), the transfer coefficient $TF_z(r)^{appl}$ is defined as the ratio of depth dose rate with applicators to that without applicator as a bare probe at the same depth from the isocenter, which is used in the calculation of the XRS depth dose rate of different applicators. The INTRABEAM system only provides the transfer coefficient value for spherical and needle applicators. The average difference in transfer coefficient between the measurement and system data for spherical, flat and needle applicators is -2.6% ~ 2.4% (range: -8.9% ~ 4.2%), 0.89% ~ 2.91% (-1.98% ~6.34%) and -3.79% (-6.17% ~ 0.75%), respectively.

The measurement range of transfer coefficient for spherical applicators in diameter of ≤ 3 cm is 0.57~0.88, which increases with the depth increasing. The mean deviation of measured value and system value is -2.6% ~ -2.2%, which decreases with the increase of depth when it is close to the isocenter. The transfer coefficient for spherical applicators in diameter > 3 cm group is in 1.21 ~ 1.58,which decreased quickly with the depth increasing, and the mean deviation of the measured value and system value is 0.8% ~ 2.4%. The trend in change of transfer coefficient is not obvious in different size of spherical applicator.

The transfer coefficient for the flat applicator is in the range of 0.86 to 2.15, which decreases with the increase of measurement depth. The transfer coefficient value is small for applicators with large diameter; it becomes even smaller when the applicator is close to the surface and larger when the applicator is far away from the surface.

Table 1. Comparison of depth dose (Gy) when 10 Gy is delivered at reference point of 5.0 mm from the surface of the applicators of different shapes with different size.

Applicators	Diameter (cm)	Surface dose rate (Gy/min)	Depth (mm)					
			0	2	5	10	15	20
Spherical	1.5	3.58	28.6	18.1	10.0	4.7	2.6	1.6
	2.0	2.07	24.7	16.7	10.0	5.1	3.0	1.9
	2.5	1.34	22.0	15.6	10.0	5.4	3.2	2.1
	3.0	0.92	20.0	14.8	10.0	5.7	3.5	2.3
	3.5	1.33	22.5	15.7	10.0	5.4	3.3	2.0
	4.0	0.91	20.2	14.8	10.0	5.7	3.5	2.3
	4.5	0.64	18.7	14.3	10.0	6.0	3.8	2.5
	5.0	0.48	17.9	13.9	10.0	6.1	4.0	2.8
Flat	1.0	9.93	55.6	24.4	10.0	3.5	1.7	0.9
	2.0	2.51	31.9	18.9	10.0	4.5	2.4	1.4
	3.0	1.12	24.6	16.6	10.0	5.1	3.0	1.9
	4.0	0.65	21.3	15.4	10.0	5.6	3.4	2.2
	5.0	0.47	19.8	14.6	10.0	5.8	3.6	2.4
	6.0	0.37	18.8	14.3	10.0	6.0	3.8	2.5
Needle	0.4	287.9	242.5	48.4	10.0	2.1	0.8	0.4

The transfer coefficient for the nee dle applicator is 1.07~1.73 which decreases with the increase of measurement depth.

Repeatability of the dosimetry

The depth dose rate are measured 3 times for bare probe, the spherical applicator in diameter of 4.5 cm, the flat applicator in diameter of 5.0 cm and the needle applicator. For most majority of measurements, the maximum deviation at specific measurement position is 0.1% ~ 1.3%, 0.2% ~ 0.7%, 0.6% ~ 2.2% and 0.3% ~ 2.1%, respectively. It shows relative poorer repeatability at the depth near the surface or 2 cm away from the surface of the applicator.

The isotropy is measured 3 times for the spherical applicator in diameter of 4.5 cm and the needle applicator. The range of relative deviation for each measurement points is -1.6% ~ 2.6% and -1.7% ~ 2.0%, respectively. Repeatability is good with the same change trend of all measurement value for these two applicators.

Discussion

The tools used for INTRABEAM IORT dose measurement include water phantom/ionization chamber [7,11], film/solid water phantom [11], thermo-luminescence dosimeter [12], etc. It has been reported that water phantom/ionization chamber has the highest accuracy among those instruments [10]. Our data have demonstrated that the deviation between the measurement values of depth dose rate for the XRS or different applicators to system data is within some range between 5% and 10%. The uncertainty remains large due to the property of low energy photons with wide spectrum of 0-50 kV such as high surface dose and sharp gradient which can be influenced by many factors.

Armoogum et al [13] analyzed the factors that affect the measurement including temperature and atmospheric pressure correction factor, ionization chamber position deviation, ionization chamber current, the chamber/dosimeter calibration factor, output drift and calibration of absorbed dose. Among these factors position deviation is the most significant one. The estimation of total uncertainty for all these factors can reach to ±10.8%. Our data have shown that the dose gradient at 3 mm and 10 mm from the XRS isocenter is 60%/ mm and 24%/ mm which may cause dose change from 2.4% to 12.0% due to 0.1 mm ~ 0.2 mm position deviation between the touch point of the XRS lower surface and the measuring chamber caused by subjective judgments of researchers.

The lower value of depth dose rate for 40 kV XRS measured at the same depth compared with the 50 kV XRS is due to the characteristics of sharp attenuation in the medium for low energy photon with wide spectrum. That may be the reason of unusual ratio of depth dose rate for the 40 kV and 50 kV XRS at the depth near or far away from the surface. The uncertainty for measurements is caused by sharp dose gradient and low dose rate with minimal amount of charge. Deviation between depth dose rate of different tube currents with constant tube voltage of 50 kV and the theoretic value is ±2%. The discrepancy in measurements obtained between commissioning and clinical application of the system for 4 months is small which shows in relatively good consistency.

Goubert et al [14] have reported that the dose distribution measured with radiochromic film is not uniform near the surface of the flat applicator with 1.7~3.0 times center point dose at the peripheral area, whereas the heterogeneity decreases with the diameter increasing. The dose distribution becomes uniform at 4 ~ 8 mm away from the surface of the flat applicators. The difference in dose distribution may be significant if the head of applicator is not perpendicular to the radiation plane or there exists air gap between human tissues and applicator. It is critical to note that each flat applicator must be measured individually prior to clinical use since the transfer coefficient is not provided by the manufacture.

The needle applicator is mainly applied for the treatment of spinal metastasis with small volume of lesion which characterizes with an extremely sharp dose gradient and a complex component of energy spectrum of 1~50 kV X ray due to its specific configuration. The deviation between the calculation and real depth dose rate in human body cannot be ignored due to its significant attenuation in the bony tissue than that in water whereas the correction coefficient of dose absorption in the inhomogeneous tissues is not provided [15]. Monte-Carlo algorithm used in dose calculation of the non-uniform tissues may be a feasible scheme [16]. Due to the characteristic of sharp dose gradient for needle applicator, the region close to the applicator may expose to extremely high dose, special consideration should be taken when the spinal cord is in the vicinity of the needle applicator.

Our data have shown that the range of treatment is approximately 0.5 cm while deeper tissues can be well protected. External irradiation should be considered to ensure the local tumor control when the surgical edge is positive or tumor tissue remains incompletely excised. More consideration should be taken when applicator in small size is used to deliver IORT since the absorbed radiation dose will be attenuated significantly with the existence of air gap and the range of treatment becomes smaller with 0.2~0.5 cm. The difference in dose distribution between different XRS is large, especially between the older model and newer one[14]. Due to the limitation in measurement condition, only the depth dose rate and isotropy for different applicators in water phantom have been tested; while the measurements in two dimensional dose distribution, in the existence of air gap or tilt condition are not performed.

Conclusion

In summary, the measurements of dose rate for the low energy X-ray IORT system under different tube voltage/tube current are in relatively good consistency with the system data. The dosimetric performance changes significantly with the depth of measurement and the type and diameter of the applicators, which should be taken into account in clinical application.

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