DOSE NON-LINEARITY OF THE DOSIMETRY SYSTEM AND POSSIBLE MONITOR UNIT ERRORS ON MEDICAL LINEAR ACCELERATORS USED IN CONVENTIONAL AND INTENSITY-MODULATED RADIATION THERAPY

by

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The purpose of this work is to study dose non-linearity in medical linear accelerators used in conventional radiotherapy and intensity-modulated radiation therapy. Open fields, as well as the enhanced dynamic wedge ones, were used to collect data for 6 MV and 15 MV photon beams obtained from the VARIAN linear accelerator. Beam stability was checked and confirmed for different dose rates, energies, and application of enhanced dynamic wedge by calculating the charge per monitor unit. Monitor unit error was calculated by the two-exposure method for open and enhanced dynamic wedge beams of 6 MV and 15 MV photons. A significant monitor unit error with maximum values of 2.05931 monitor unit and 2.44787 monitor unit for open and enhanced dynamic wedge beams, respectively, both energy and dose rate dependent, was observed both in the open photon beam and enhanced dynamic wedge fields. However, it exhibited certain irregular patterns at enhanced dynamic wedge angles. Dose monitor unit error exists only because of the overshoot phenomena and electronic delay in dose coincident and integrated circuits with a dependency on the dose rate and photon energy. Monitor unit errors are independent of the application of enhanced dynamic wedge. The existence of monitor unit error demands that the dose non-linearity of the linear accelerator dosimetry system be periodically tested, so as to avoid significant dosimetric errors.

Key words: monitor unit error, dose non-linearity, linear accelerator, enhanced dynamic wedge

INTRODUCTION

The concept of timer error (TE) is an established fact for Co-60 teletherapy units. It arises when the source is partially obscured due to the mechanical moment of the source in transition from the off to on position [1-5]. The concept of this type of timer error is applied to those machines in which the mechanical moment of the radioactive source is involved in irradiating patients, *i. e*., brachytherapy, Co-60 teletherapy units, *etc*. [2, 6]. However, the overshoot effect caused by the control loop in the Varian DMLC system (V4.8) (*i. e*., ~65 ms) to monitor and halt the irradiation of a segment may result in a fractionally larger monitor unit (MU) than the planned. As a result, the actual MU delivered may differ from the planned. The effect depends on the delivery rate (MU per minute) and is most pronounced in low-dose regions. Simply, the overshoot is the delivery rate multiplied by the control loop delay time in terms of absolute MU [7]. Although X-ray beams in linear accelerator (LINAC) are produced in a different manner from those produced by the Co-60 teletherapy machine, TE/monitor unit error (MUE) can still be applied to LINAC, as well [2, 7]. Different approaches by different manufacturers have been applied in order to render dose integration and therapeutic techniques accurate enough to give a low probability of MUE [2]. But, due to the electronic delay in dose integration and coincidence circuits, the timer may not measure the treatment time accurately, producing an error in the dose delivery to the patient

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[2, 7]. The difference between irradiation time and the time calculated by the dose integrated circuits can be referred to as MUE on LINAC. To ensure an accurate delivery of the prescribed dose to the patient, the MUE LINAC must be calculated and applied to irradiation time [8]. The international atomic energy agency (IAEA) has recommended a quality control (QC) test (tolerance < 1%) for measurements of TE on a Co-60 teletherapy unit, but no such recommendations or guidelines have been set or approved for LINAC [3, 4]. A general view of LINAC is that, at the moment, TE/MUE is negligible, as far as contemporary LINAC are concerned [9]. Biggs [2] investigated TE only for electron beam LINAC used in intraoperative radiation therapy. A significant energy-independent and dose-rate dependent TE has been found by him. The TE was investigated for electron energies of 6, 9, 12, and 15 MeV, with dose rates of 300 and 600 MU per minute and at all energies of 900 MU per minute and MU settings between 50 and 2000. Although Biggs has stated in his studies that TE may have serious consequences in the implementation of intensity-modulated radiation therapy (IMRT) [2], there are no experimental measurements in existence in support of his claim. His study has also failed to provide any measurements for photon beams. Moreover, the study was done for LINAC used in intraoperative radiation therapy, involving very large dose rates options (*i. e.*, 300, 600 and 900 MU per minute), but we know that the overshoot has the most profound effect in low-dose regions [7]. The stability of the LINAC dosimetry system is very important for accurate dose delivery in conventional radiotherapy and IMRT [7]. Therefore, the study has been designed to investigate the dose non-linearity of the LINAC dosimetry system by calculating beam stability in different clinical conditions, along with MUE for 6 and 15 MV photon beams produced for conventional radiotherapy and IMRT with dose rates of 80, 160, 240, and 320 MU per minute. Beam stability and MUE were also investigated for the said purpose in the application of enhanced dynamic wedge (EDW) on a VARIAN LINAC.

METHODS AND MATERIALS

A dosimetry system inside the treatment head of a medical LINAC is used to measure MU delivered to the patient. It consists of two separately sealed dual transmission ionization chambers with completely independent biasing power supplies and readout electrometers, termed as primary and secondary chambers. To measure the additional parameters like beam energy, radial and transverse beam flatness and symmetry, the ionization chambers have been designed so that their electrodes are divided into several sectors. The design of the electrodes and sectors depends on the manufacturer of the machine. Literature shows that the response of electronic circuits in high radiation fields is dose rate-dependent [10, 11]. The peak voltage (or current) of the transistors and diodes is proportional to the dose rate over a certain range of dose rates, with evidence of some non-linear behavior [12]. Silicon diodes, especially PIN diodes, are regularly used as beam monitors and dosimeters in LINAC systems, because their photocurrent is proportional to the dose rate and the total charge collected is proportional to the total dose [9, 13]. On the other hand, the method of EDW is a treatment delivery technique of Varian LINAC in which the wedged dose profile is produced by the motor- controlled motion of a collimator jaw from the open to the closed position during treatment [14-17]. During treatment, different parts of the field are exposed to primary beams for different time durations, while the jaw speed and dose rate are continuously changed during irradiation [17]. Seven types of EDW with wedge angles of 10°, 15°, 20°, 25°, 30°, 45°, and 60° can be produced by Varian CLINAC 2100C.

The dosimetry system should be linear, accurate and capable of turning off the radiation beam when the programmed irradiation time passes, so as to ensure an accurate dose to the patient. To check the linearity and accuracy of the dosimetry system, a FC65G (formally Wellhofer, active volume of 0.65 cm^3) Farmer-type ionization chamber attached to a PTW UNIDOS E universal dosimeter and a Wellhofer Blue Water Phantom was used to measure the charge for different MU (*i. e.*, 1-500 MU) setups. The phantom has a positional accuracy of 0.5 mm per axis and a reproducibility of 0.1 mm. Measurements were performed for both open (non-wedged) and EDW fields with a fixed field size (10 cm 10 cm) at 100 cm SSD for 6 MV and 15 MV photon beams produced by a Varian CLINAC 2100C. In open fields, the measurements were taken on the central axis, at a depth of 10 cm for MU settings of 1, 5, 10, 25, 50, 100, 150, 200, 250, 300, 350, 400, and 500 MU at dose rates of 80, 160, 240, and 320 MU per minute. In the present study, four wedges with wedge angles of 15°, 30°, 45°, and 60° were used. For EDW fields, measurements were made for MU settings of 25, 50, 100, 150, 200, 250, 300, 350, 400, and 500 MU. As the dose rate continuously changes during irradiation, the dose rate effect cannot be studied for EDW fields. The chamber was placed in a 0.5 cm gap at the thin end of the EDW angle, so as to avoid the decrease in beam intensity due to the presence of EDW. To compare the results of MUE for the EDW beams to the corresponding reference open beams ones, it is needed that the experimental conditions for both must be the same. Therefore, the open beam measurements were performed for the same experimental set-up as settled for the EDW fields.

The charge per MU was calculated for all available photon energies (*i. e.*, 6 MV and 15 MV) and dose rates (*i. e.*, 80, 160, 240, and 320 MU per minute), for

MU settings between 1-500 MU and 25-500 MU for open beams and EDW beams, respectively, in order to analyze beam stability. The MUE was calculated for both open and EDW fields of 6 MV and 15 MV photon beams, by means of the two-exposure method used for TE in the Co-60 teletherapy unit, as described in eq. 1 [1, 5].

$$MUE \quad \left|\frac{MU_1 R_2 \quad MU_2 R_1}{R_1 \quad R_2}\right| \tag{1}$$

where R_1 and R_2 are the dose readings obtained for MU settings, MU_1 and MU_2 respectively, on LINAC. Equation 1 was used to calculate the MUE for all possible combinations of MU.

RESULTS AND DISCUSSION

The calculated relative charge per MU (nC/MU) at all available dose rates (*i. e.*, 80, 160, 240, and 320 MU per minute) for open fields of 6 MV and 15 MV photon energies, is shown in fig. 1. A constant and linear behavior of nC/MU against MU is observed for dose rates at both energies above the 25 MU setting, as shown in fig. 1. In contrast, a slightly variable behavior is observed while plotting nC/MU against MU below the 25 MU settings, as shown in fig. 1, for all dose rates and both energies. Results show that the beams are well stable above the 25 MU settings. Furthermore, no effect of either energy or dose rate was observed on nC/MU.

The calculated relative charge per MU (nC/MU) for the application of EDW fields of 6 MV and 15 MV photon energies is shown in fig. 2. The same graphical pattern while plotting nC/MU against MU for EDW fields as open beams is observed for both 6 MV and 15 MV, as shown in fig. 2(a) and (b). The variation in nC/MU against MU for both energies studied shows beam stability with the application of EDW. The beam stability for a particular dose rate and MU settings < 22 MU cannot be checked because the dose rate does not remain constant and constrained on MU settings with the application of EDW.

The MUE was calculated for open fields, as well as for the implementation of EDW in photon beams of 6 MV and 15 MV (see, tabs. 1, 2). The energy effect and dose rate effect on MUE was investigated for the open fields of photon energies under study and for available dose rates (*i. e.*, 80, 160, 240, and 320 MU per minute). For open fields of 6 MV and 15 MV photon beams, the MUE was calculated at different dose rates (*i. e.*, 80, 160, 240 and 320 MU per minute) with the help of equation 1 (*i. e.*, the two-exposure method). The results are summarized in tab. 1. A significant MUE with a maximum error of 2.05931 MU was observed for open photon beams of 6 MV and 15 MV energies (tab. 1). Figure 3 shows that, as the dose rate increases from 80 to 320 MU per minute, the mean value of MUE for 15 MV decreases while, in contrast, no regular pattern for the mean value of MUE can be ob-

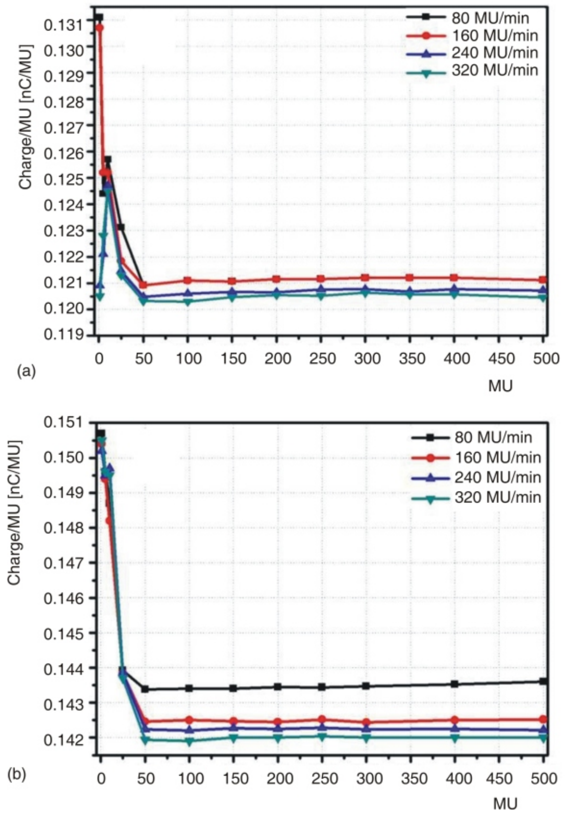

Figure 1. Charge per MU (nC/MU) *vs.* MU delivered at listed dose rates in open field of (a) 6 MV photon beams and (b) 15 MV photon beams

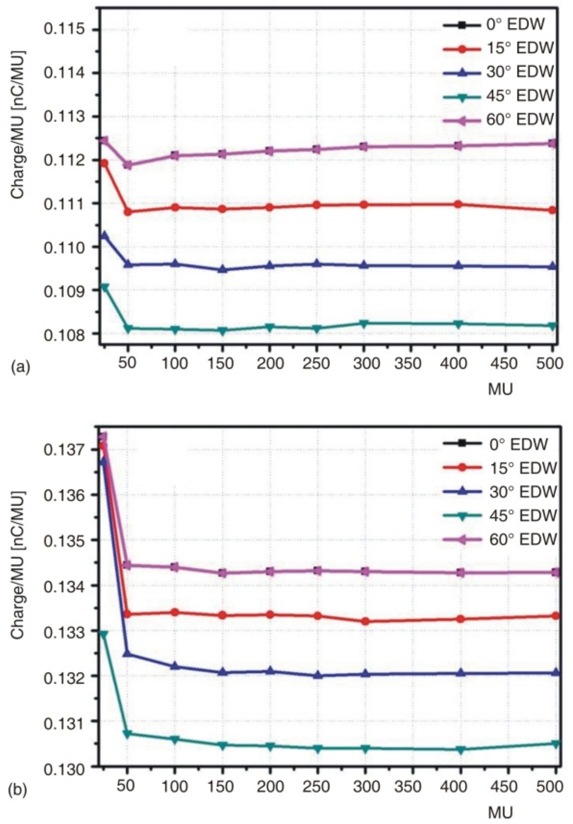

Figure 2. Charge per MU (nC/MU) *vs.* MU delivered in listed EDF fields (a) of 6 MV photon beams and (b) 15 MV photon beams

Table 1. Minimum, maximum, and mean standard deviations of MUE, calculated by two-exposure method for tabulated dose rates for an open field of 6 MV and 15 MV photon beams

Energy [MV]	Dose rate MU/min	MUE by two-exposure method (MU)			
		Minimum	Maximum	Mean	
6	80	0	1.62338	0.3614	0.37791
	160	0	1.3245	0.217	0.24803
	240	0.04143	2.05931	0.3112	0.41471
	320	0.01186	1.91667	0.413	0.4389
15	80	0	1.04239	0.2089	0.24184
	160	0	0.91549	0.1412	0.21418
	240	0	0.49296	0.0924	0.11881
	320	0	0.42313	0.0767	0.10276

Table 2. Minimum, maximum, and mean standard deviations of monitor unit error (MUE), calculated by two-exposure method for tabulated wedge angles of 6 MV and 15 MV photon beams

Energy [MV]	EDW [angle]	MUE by two-exposure method (MU)			
		Minimum	Maximum	Mean	
6	0	0.08913	0.97691	0.37064	0.20218
	15	0	2.44787	0.26549	0.46895
	30	0	0.45704	0.15972	0.15905
	45	0	1.5625	0.26579	0.32772
	60	0	0.84507	0.1946	0.20093
15	0	0.17805	1.16742	0.44653	0.22891
	15	0	1.35747	0.2401	0.33101
	30	0.01082	0.75988	0.20354	0.13424
	45	0	1.9084	0.25401	0.34438
	60	0	1.1655	0.23924	0.31073

served for the 6 MV photon beam. Furthermore, smaller mean values of MUE were observed for 15 MV, as compared to the 6 MV photon beam at the same dose rate, as shown in fig. 3. Over all, the MUE has increased behavior with a decrease in energy. MUE was also calculated for the implementation of EDW (*i. e*., 150, 300, 450, and 600), for both 6 MV and 15 MV photon beams (tab. 2). A significant MUE with

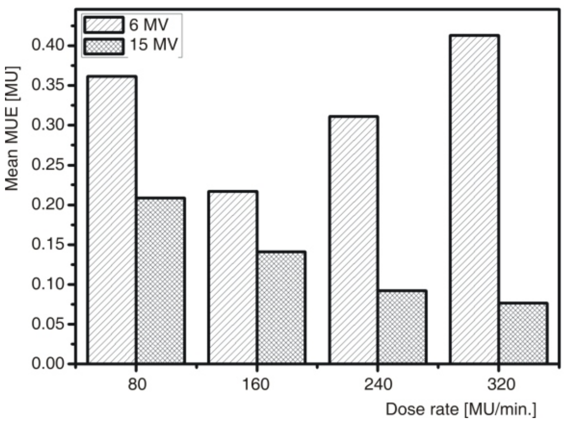

Figure 3. Mean MUE for different dose rates calculated with the two-exposure method for open beams of 6 MV and 15 MV

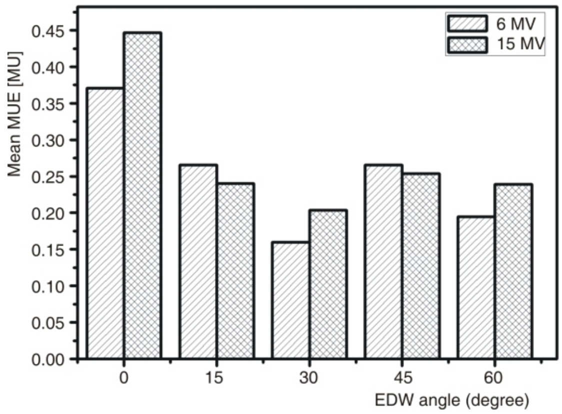

Figure 4. Mean MUE calculated by two-exposure method of the different EDW angles of 6 MV and 15 MV photon beams

a maximum value of 2.44787 was observed in EDW fields, for both 6 MV and 15 MV photons beam energies. When the mean value of the MUE trend was compared with the increase in the EDW angle, no regular pattern was found as the EDW angle increased from 150 to 600, for both 6 and 15 MV photon beams, as shown in fig. 4. No relation of MUE was established with the application of EDW from the above results. This goes to show that the MUE is independent of the application of EDW for both energies. The variation in MEU exists due to the fact that, during its application, the dose rate continuously changes.

The actual dose coming out of the machine needs to be reliable and predictable in order to fully realize the benefits of a more sophisticated and advanced treatment planning and image guidance techniques and ensure an adequate dose to the tumor. However, the dosimetry system used inside the treatment head of the LINAC to measure the MU to be delivered to the patient is continuously exposed both to high-energy X-rays produced by the machine and the secondary neutrons produced as a result of X-rays. In short, the system always operates in a high radiation exposure environment. Hence, it is vital to check the MUE from time-to-time, so as to remove possible errors in the readings of the planned dose to the patients that might occur due to a continual exposure to radiation. This not only confirms the correct dose to the patient, but also ensures the precise use of the state-of-the-art equipment developed for the treatment. MUE was also calculated for the application of EDW, because dynamically-wedged fields are generated by the sweeping motion of a field-defining element (jaw) during beam-delivery time. This mechanical motion requires a close synchronization with the dosimetry system and, thus, the said interaction has the potential of leading to deviations from the intended dose. Similar effects have been identified in dynamic delivery systems using MLC motion to modulate the beam during beam on. An investigation into this effect for dynamic wedges has not yet been reported in literature. The present study is a footnote for such a situation.

Our results have shown that the beam is highly stable at all energies, dose rates and EDW. Furthermore, they prove the linear behavior of the dosimetry system inside the treatment head of the LINAC. As the beam is highly stable at all energies, dose rates and EDW, the MUE exists only because of the overshoot phenomena and electronic delay in the dose coincident and integrating circuits. The effect of MUE on dose rates is greater at low dose rates, as the overshoot phenomenon is more prominent at low dose rates [7]. MUE is independent of the application of EDW, because the circuit designed for jaw movement and control during its application works independently of the dose integrated and coincidence circuits. The total MU delivered is always the same, as in open beam therapy the dose integrated and coincidence circuit's signal terminates the beam independently of the EDW control loop. It may, thus, be concluded that MUE is independent of the application EDW, while it shows some dependency on the dose rate and energy of the photon beam. As the electronic circuits are highly sensitive to radiation and the fact that radiation may result in displacement damage in these circuits [9], the check of the dose linearity of the LINAC dosimetry system can act as a quality control test for this type of damage.

CONCLUSIONS

Significant MUE with maximum values of 2.05931 MU and 2.44787 MU for open and EDW beam, respectively, have been observed. They are dose rate and beam energy dependent, while independent of the application of EDW. Furthermore, it has been observed that the beam is stable with the application of EDW, both in relation to the dose rate or either of the two energies. The MUE is independent of the application of EDW, because the EDW control loop is independent of dose integrated and coincidence circuits. Therefore, the presence of MUE is due to the overshoot phenomenon of electronic delay in dose coincident and integrated circuits with a dependency on photon energy. The existence of MUE requires that every LINAC be periodically tested for the existence of possible MUE, as a means of avoiding significant dosimetry errors. Furthermore, periodic checks of the dose linearity of LINAC dosimetry systems may serve as a quality control test for the damage in dose integrated and coincidence circuits, due to the continuous exposure to radiation.

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AUTHOR CONTRIBUTIONS

Study was designed by W. Muhammad, and experiments were also carried out by W. Muhammad. Theoretical analysis was carried out by W. Muhammad, S. Hoon Lee, K. Alam, M. Maqbool, and G. Khan. All the authors analyzed and discussed the results. The manuscript was written by W. Muhammad and the figures were prepared by K. Alam and G. Khan.

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НЕЛИНЕАРНОСТ ДОЗЕ ДОЗИМЕТРИЈСКОГ СИСТЕМА И МОГУЋЕ ГРЕШКЕ МОНИТОРСКЕ ЈЕДИНИЦЕ МЕДИЦИНСКИХ ЛИНЕАРНИХ АКЦЕЛЕРАТОРА КОРИШЋЕНИХ У УОБИЧАЈЕНОЈ И ПРОМЕНЉИВОГ ИНТЕНЗИТЕТА ТЕРАПИЈИ

У раду је проучена нелинеарност доза код линераних акцелератора који се користе у уобичајеној радиотерапији променљивог интензитета. Коришћена су отворена поља и поља са динамички појачаним пробијањем за прикупљање података из фотонских снопова енергија 6 MeV и 15 MeV на VARIAN линеарном акцелератору. Одређивањем количине наелектрисања по мониторској јединици и нормализоване количине наелектрисања по мониторској јединици, проверена је и потврђена стабилност снопа за различите јачине доза, енергија и примену динамичког пробијања. Грешка мониторске јединице израчуната је методом двоструког излагања за отворене и динамичке појачане снопове фотона енергија 6 MeV и 15 MeV.

Код оба снопа је уочена значајна грешка мониторских јединица са максималним вредностима од 2.44787 мониторских јединица за динамички појачани сноп и са изразитом зависношћу од енергије и јачине дозе. Грешка мониторске јединице показала је одређено нерегуларно понашање од угла динамички појачаног пробијања. Она постоји само због феномена пребацивања и кашњења у коинцидентним интегрисаним колима, уз зависност од енергије и јачине доза, а независна је од примене динамичког пробијања. Њено постојање захтева периодично тестирање нелинеарности линеарних акцелератора како би се избегле значајне дозиметријске грешке.

Кључне речи: грешка мониторске јединице, нелинеарност дозе, линеарни акцелератор, динамички појачано пробијање