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A Comparison of dosimetric parameters between IAEA TRS-398, AAPM TG-51 protocols and Monte-Carlo simulation

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Background: Two protocols of AAPM TG-51 and IAEA TRS-398 were compared followed by a measurement and Monte Carlo simulation of beam quality correction factor, $K_{Q,}$ AAPM TG-51 and IAEA TRS-398 protocols were compared for the absorbed dose to water for $D_{W,}$ and K_Q parameters. ***Materials and Methods:*** Dose measurements by either protocols were performed with cylindrical and plane parallel chambers for 6 and 18 MV photons, and 6, 9, 12, 15, 18 MeV electron clinical beams were traced to the calibration factor of Iranian secondary standard dosimetry laboratory. MCNP-4C simulation of depth doses, beam profiles and K_Q factors were validated typically for 18 MV and 12 MeV beams by experimental measurements. ***Results:*** The differences between simulation and measurements were 0.07% for beam profile, -2.60% and 1.19% for 12 MeV build up and linear portion of the depth dose curve, respectively. The figures of merit for 18 MV were about -4.17%, -1.62% and 0.38%. The differences of K_Q's between simulation and measurement of 12 MeV, and 18 MV beams for TG-51 were -0.194% and 0.169%, and for TRS-398, they were about -0.465% and 0.097%, respectively. ***Conclusion:*** These differences between the two dosimetry protocols (IAEA TRS-398 & AAPM TG-51) from the point of absolute dosimetry were not significant at least when they were used under the same calibration procedure. The good agreement between Monte Carlo and measurement may also be even more important regarding the contribution into the development of radiotherapy treatment planning system, based on Monte Carlo procedures. **Iran. J. Radiat. Res., 2012; 10(1): 43-51**

Keywords: *Clinical dosimetry, TRS-398, AAPM TG-51, Monte Carlo simulation.*

INTRODUCTION

Higher precision of dose delivery is the first approach for the development of a dosimetry protocol. However, two criteria should be considered for the selection of a clinical dosimetry protocol. First a calibration dosimetry method normally traceable to regional standard dosimetry laboratory and, secondly to be practical and easy to use in clinic; so, that radiotherapy physicists will spend a little time for absolute dosimetry of various beams (1-3).

Air kerma calibration factor In Iran is provided by secondary standard dosimetry laboratory (SSDL) for ^{60}Co beam quality. Radiotherapy departments are applying the ion chamber calibration factor to different photon and electron beams qualities. On the other hand, the success of radiotherapy depends on the absorbed dose within the target volume with no more than ± 5 % uncertainty (1). Since it is possible to delineate the target and other critical structures, using sophisticated diagnostic imaging modalities, there is a need to evaluate the absorbed dose accurately to maximize the target dose and minimize the normal tissue dose. However, it requires the measurement procedures in calibration laboratories as much possible as to be comparable to the user condition.

Different studies have investigated the correspondence of the two ionizing radiation dosimetry protocols of American Association of Physicists in Medicine Task Group-51

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(AAPM TG-51) and International Atomic Energy Agency Technical Report Series-398 (IAEA TRS-398) through measurement by cylindrical and plane-parallel ionization chambers [4,5]. In this study, we have studied the differences of the absorbed dose to water and the beam quality factor of these two protocols with calibration factors traced to the regional (SSDL).

The formalism and dosimetry procedures in the new TG-51 and International Atomic Energy IAEA TRS-398 protocols were based on the use of an ion chamber with a ^{60}Co absorbed-dose to water calibration factor, $N_{D,W}^{^{60}Co}$, and the beam quality correction factor, K_Q, for the user beam [6].

However, the compatibilities of the measurements and Monte Carlo (MC) simulation of depth doses (DD's), as well as beam profiles of 18 MV and 12 MeV radiations were analyzed typically for upcoming projects in which we would propose the comparison of the measurement by protocols with exact simulation of dose distribution for even more precise dosimetry.

MATERIALS AND METHODS

IAEA TRS-398 and the AAPM TG-51 have published different protocols for the calibration and/or measurement of clinical beams. These protocols are based on the use of an ionization chamber in terms of absorbed dose to water in standard laboratories and reference beam quality. Absorbed doses to water and beam quality factors were measured and then their ratios of AAPM TG-51 / IAEA TRS-398 were calculated. Measurements were performed within a computer-control scanner water tank of 40 × 40 × 40 cm^3 (MP2 beam analyzer, PTW Freiburg, Germany). For central axis depth dose, the measurements were performed with a PTW Markus plane parallel chamber and a 0.6 cm^3 PTW 30001 cylindrical chamber; both chambers were connected to a PTW Unidos E electrometer. The reference setup corresponded to a 10 × 10 cm^2 field size and SSD = 100 cm. The scanning system had a position accuracy of ≤ 1 mm and a reproducibility of ≤ 0.1 mm. Measurements were made in 6 and 18 MV photons, as well as 6, 9, 12, 15 and 18 MeV electron beams.

In this work, the MCNP-4C code [7] was used to run the 18 MV photon and 12 MeV electron beams spectra from the head of a Varian Clinac 2100 C/D linear accelerator to obtain the correspondence of dosimetric properties (e.g. depth doses and beam profiles).

The simulated models included the bremsstrahlung target, the primary collimator, the vacuum window, the flattening filter, the monitor ion chamber, the mirror, the scattering foil and applicator (in the case of 12 MeV), as well as the upper and lower jaws. Beam monitoring chamber (more details reported by Duzenli *et al.* 1993) [8] and flattening filter (only in the case of 18 MV) were accurately modeled due to the fact they were the main sources of contaminating electrons. For the electron beam, the target was not present, scattering foil replaced the flattening filter and the primary collimator was also omitted from the electron beam simulations since it did not influence the beam significantly. For electron beams the applicator and a field defining insert in its bottom scraper was also included. This detailed description of the geometry required for the accurate simulation was provided by the manufacturer.

The exact energy and radial spread of the hitting electrons to the target were unknown and must have been obtained by calibrating each spectral distribution against the corresponding depth dose curve and profiles. It should be noted that the central axis -depth dose curves have been dependent to the hitting electron energy while the dose profiles (especially for larger field sizes) were more affected by the radial spread of these electrons. The range of the primary mean electron energy was ranged from 17.7 to 18.4 MeV. The final incident electrons had a Gaussian energy distribution with a full width at half maximum (FWHM) of 1 MeV and centered at 18.2 MeV for the 18 MV photon beam. The electron beam radial intensity distribution was also set to be a Gaussian with the FWHM of 1.4 mm.

A study reported by Ding *et al.* 1995 [9] showed that there has been little difference in the depth dose when using incident electrons which were either mono-energetic or having symmetric energy spectra. The incident electron energy on the exit window is usually higher than the nominal beam energy. For 12 MeV, we started the simulation by selecting incident electron energy to match with measured value of R_{50} for the 10 × 10 cm^2 applicator. The model fine-tuning process resulted in peak energy of 12.25 MeV for 12 MeV electron beam. The FWHM was set to 0.103 cm. The number of electrons in the primary beam was set to 10^8. The cutoff energies of electrons and photons were set to 100 KeV and 10 KeV respectively. No photon interaction forcing and no Rayleigh scattering were used. The CPU used for the simulation was a Pentium IV with 2.5 GHz processors. Such simulations can also model the interactions which electrons undergo within the treatment head of the linear accelerator, allowing the dose at each point in the tissue to be broken down into several components, including that from contaminant photons [10]. The maximum statistical uncertainties of the results were about 2 % and 3% at the deeper depth (20 cm) of DD, and with more distance from the central axis (15 cm), respectively. For depth dose calculations in water phantom, a cylinder with a radius of one-tenth the size of the open field size was defined and divided into scoring cells with 2 mm height along the beam central axis. For beam profile calculations the primary cylinder was located at considered depth vertically to the beam central axis with the radius of 2 mm. Therefore, the dose resolution was 2 mm in this study. The set up depicted in figure 1, is the simulated geometry for the Varian 2100C/D linac and water phantom.

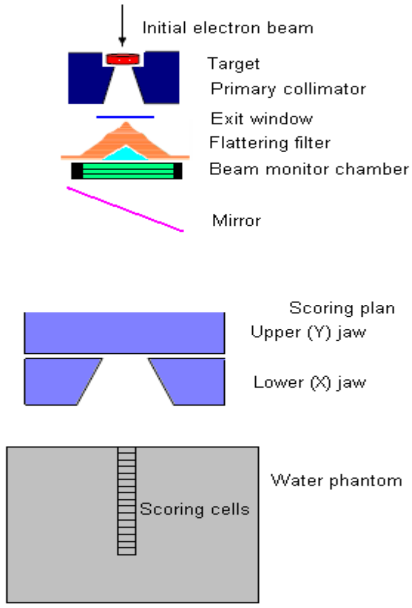


Figure 1. Schematic representation of the Monte Carlo models for the Varian 2100C/D linear accelerator geometry in photon mode.

To compare the simulation and measurement data of DD's and beam profiles, the average percent of difference was estimated through equation 1 [11]. For this purpose, a FORTRAN program was released which can find point to point difference in percent and then average them out for the range of measured depth on the depth dose and/or beam profile:

$$\text{Average difference\%} = [(\text{calculation} - \text{measurement})/\text{measurement}] \times 100 \qquad (1)$$

Dosimetry Formalism

The dosimetry system was calibrated by SSDL of Iran at a reference condition in a ^{60}Co gamma-ray beam. To measure the absorbed dose to water, the calibration factor, $N_{D,W}$, was obtained to be 1.33 and 0.05335 Gy/nC for plane-parallel and cylindrical chambers, respectively.

According to TRS-398, the absorbed dose to water at the reference depth, Z_{ref}, in water for a reference beam of quality Q_0 (^{60}Co) is equal to:

$$D_{W,Q} = M_Q N_{D,W,Q_0} K_{Q,Q_0} \qquad (2)$$

Where, M_Q is the reading of the dosimeter under the reference condition which should be corrected to influence quantities such as polarity and recombination effects and $N_{D,W,Q0}$ is the calibration factor in terms of absorbed dose to water of the dosimeter obtained from a standard laboratory at the reference beam quality, [12]. When a dosimeter is used in a beam quality Q different from that used for calibration, Q_0, the absorbed dose to water has to be corrected for the beam quality factor, which corrects the effect of the difference between the reference beam quality Q_0 and the actual user quality Q [13].

The TG-51 protocol provides a formulation at beam quality Q and for a chamber calibrated at ^{60}Co gamma-rays energy that the absorbed dose to water at the reference depth in a beam of quality Q is obtained:

$$D_W^Q = MK_Q N_{D,W}^{60\,Co} \tag{3}$$

where K_Q converts the absorbed dose to water calibration factor for the ^{60}Co beam, $N_{D,W}^{60\,Co}$ instead of the calibration factor of an arbitrary beam of quality Q [14]. For electron beams, K_Q is written as a product of three factors;

$$K_Q = P_{gr}^Q K'_{R_{50}} K_{ecal} \tag{4}$$

where K'_{R50}, K_{ecal} and $P_{gr}{}^Q$ are the electron quality conversion factor, photon-electron conversion factor and gradient correction factor, respectively [14]. In calibration process, influencing quantities should be properly corrected. They are the quantities not being considered in the measurement, but yet influencing the quantity under measurement. These might be different in nature such as pressure, temperature and polarization voltage. Also, they may also arise from the dosimeter and / or the radiation field (e.g. beam quality, dose rate, field size, depth in a phantom) [13].

RESULTS

The findings on quality correction factors and absorbed dose to water for 6 and 18 MV photon beams of Varian 2100 C/D accelerator are given in table 1. The TG-51/ TRS-398 value for the absorbed dose to water at field size of 10×10 cm^2 were obtained to be 0.994 and 0.995 for 6 and 18 MV photons (SD<0.0006), respectively.

Typical results of percentage depth dose and beam profile for 18 MV photons obtained by measurement and Monte Carlo simulation are shown altogether in figure 2. The comparison shows that the difference in the semi-linear part of the DD curve is equal to 0.38%. The depth dose and beam profile difference between MC calculation and measurement for 18 MV photon beam in buildup region of the DD curve and in 10 × 10 cm^2 of profile were about -1.62% and -4.17%, respectively.

Electron beams dosimetry with plane parallel ionization chamber showed the mean values of quality correction factor and absorbed dose ratios of 1.020 and 1.007, respectively (table 2). The ratio of TG-51/ TRS-398 for quantities of K_Q and $D_{w,Q}$ for 12, 15 and 18 MeV electron beams were obtained by 0.6 cc cylindrical ion chamber calibrated by SSDL and the related findings are shown in table 1. Measurement of electron beam by cylindrical chamber in TRS-398 is only recommended for R_{50} >4 gr/Cm^2 but in TG -51, it is possible to calculate it for 2< R_{50} <9 gr/Cm^2. The ratios of correction factors and absorbed doses for 6 and 9 MeV energies were estimated at1.024, 1.011 and 1.025, 1.012, respectively.

Comparisons of 10 × 10 cm^2 field depth-doses and profiles data were done for both 12 MeV and 18 MV beams between measurement and MC calculation. Typical results for 12 MeV electron beam obtained by measurement and MC simulation are also shown in figure 3. The difference has been 1.19% for descending part of depth dose curve and -0.07% for beam profile area in 12 MeV electron beam. The estimated difference of DD in build-up region for 12 MeV was also -2.60%. This discrepancy in build-up region could have been due to the uncertainties in measurements near the surface where there has not been any electron equilibrium, or it could have occurred by theoretical problems at an interface [15, 16]. Except for the significant differences in R_{50} and extrapolated range (R_p), the other parts of the curve showed good agreement. There was a slight discrepancy in the values of R_{50} which showed a difference of about -3.735% for 12 MeV electron beam. The difference for R_P was 0.6413% between simulation and measurement. Typically, the difference of $TPR_{20,10}$ in 18 MV photon beam was calculated to be -1.640% between simulation and measurement.

The values of K_Q are estimated from PDD's curve of both measurements and MC simulation methods, and the results were shown in tables 3 and 4. Acceptable agreements were observed between simulated and measured data in both protocols. The difference of K_Q between simulation and measurement by the TRS-398 protocol was 0.097% and its value was 0.169% for the comparison between measurement and simulation of TG-51protocol in 12MeV electron beam. The K_Q in 18MV photon beam showed differences of -0.465% and -0.194%, respectively, for TRS-398 and TG-51in comparison to MC simulation.

Table1. AAPM TG-51/IAEA TRS-398 of the k_Q and D_W for photon and electron beams measured by Farmer-type ionization chambers PTW 30001.

Energy	6MV	18MV	12MeV	15MeV	18MeV
$K_Q(\frac{TG-51}{TRS-398})$	1.001	1.002	0.978	0.977	0.978
$D_{W,Q}(\frac{TG-51}{TRS-398})$	0.994	0.995	0.995	0.994	0.994

Table 2. TG-51/IAEA TRS-398 of the k_Q and D_W for electron beams measured by plane-parallel ionization chambers (Markus).

Energy	6MeV	9MeV	12MeV	15MeV	18MeV
$K_Q(\frac{TG-51}{TRS-398})$	1.024	1.025	1.021	1.017	1.015
$D_{W,Q}(\frac{TG-51}{TRS-398})$	1.011	1.012	1.008	1.003	1.002

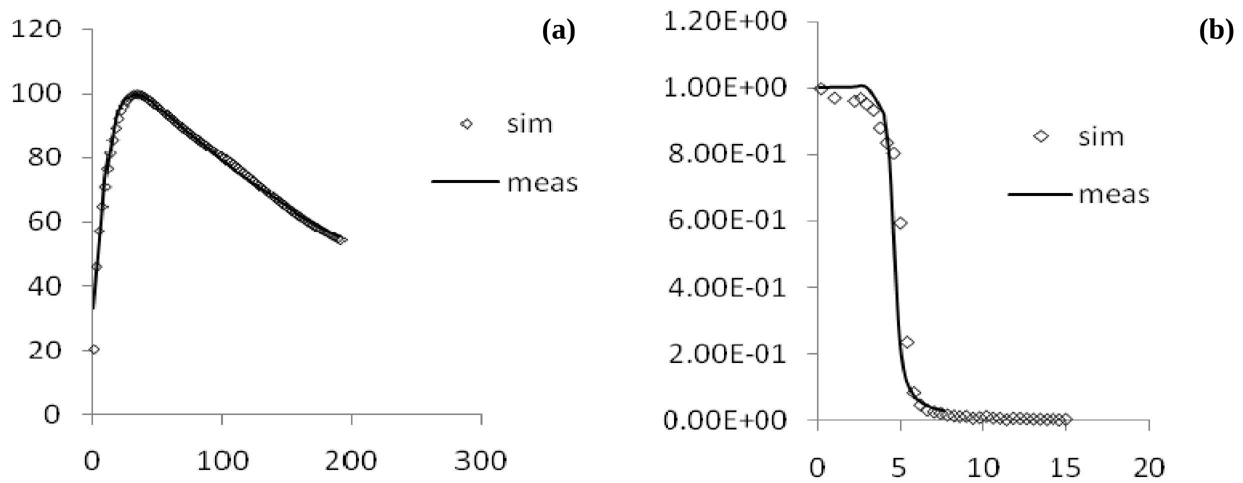
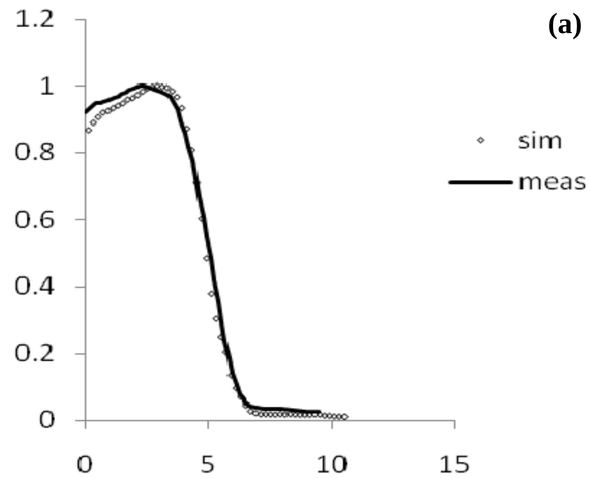


Figure 2. Comparison of Monte Carlo calculated and measured: a) central axis depth-dose distribution, b) half beam profile at depth of 4 cm for 18 MV photon beam from the Varian Clinac 2100 C/D accelerator. The field size is 10 x 10 cm² at an SSD of 100 cm.



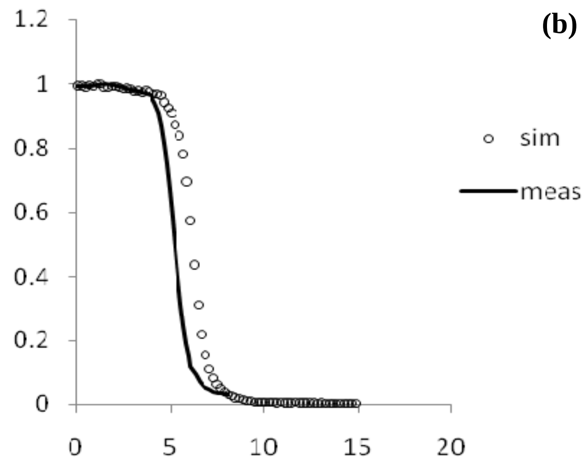


Figure 3. Comparison of Monte Carlo calculated and measured: a) central axis depth-dose distribution, b) half beam profile at depth of 2.5cm for 12 MeV electron beam from the Varian Clinac 2100 C/D accelerator. The field size is 10 x 10 cm^2 at an SSD of 100 cm.

Table 3. Estimation of K_Q value in simulation and measurement for both protocols in 12 MeV electron beam measured by Farmer-type ionization chambers PTW 300001.

Energy=12 MeV	K_Q(IAEA TRS-3980)	K_Q(AAPM TG-51)
Measurement	0.9039	0.9220
Simulation	0.9048	0.9235
%difference (sim & meas)	0.097%	0.169%

Table4. Estimation of K_Q value in simulation and measurement for both protocols in 18 MV electron beam beams measured by plane-parallel ionization chambers (Markus).

Energy=18 MV	K_Q(IAEA TRS-3980)	K_Q(AAPM TG-51)
Measurement	0.9683	0.970314
Simulation	0.9728	0.968428
%difference (sim & meas)	-0.465%	-0.1944%

DISCUSSION

The two codes of practice in this study were based on the standards of absorbed dose to water; nevertheless, there were some differences regarding the way calibrations should have been dealt with; TG-51 was based on ion chambers with absorbed dose to water calibration coefficients for ^{60}Co quality Q_0 and sets of beam quality correction factors [1]. IAEA TRS-398 provided the most general and flexible framework for calibration, allowing for very detailed possibilities which included the use of experimental or theoretical beam quality correction factors [13].

Despite the use of different protocols, all reference dose measurements in this work were traceable to Iran SSDL. Thus, this made the comparison free from differences among primary standards and methodologies used in standard laboratories.

For photon beams with 6 and 18 MV energies in 10×10cm^2 field, the measured ratios TG-51/TRS-398 of the absorbed dose to water D_w, ranged between 0.994 and 0.995 and the ratios of correction factor K_Q, were between 1.001 and 1.002. This small discrepancy was owing to the differences between the various factors that towards to

K_Q.

The averages of dose ratio and correction factor ratio for different photon beams in this study were 1.002 and 0.995, respectively. Findings showed an acceptable agreement with each other. The Same result was reported by Vargas Castrillon *et al.* 2009 [5]. They showed overall differences between IAEA TRS-398 and AAPM TG-51 of 0.2% with a single case of 0.3% for 18 MV. In another experience, it was shown that the ratios of absorbed dose with IAEA TRS-398 and AAPM TG-51 to IPSM 1990 were 1.005 [4]. They have also reported the k_Q difference of 0.4% for the case of TRS-398 theoretical k_Q factors and of 0.6% for experimental k_Q which, could be arisen from differences in the quality indices obtained by various procedures as mentioned [17]. Our results showed an acceptable agreement with the aforementioned report.

The measured ratios between the two protocols for electron beams with 6, 9, 12, 15 and 18 MeV energies in 10×10cm^2 field were ranged between 0.994 and 1.012 for D_W, and between 0.977 and 1.025 for $K_Q$when cylindrical and plane parallel chambers used for measured the direct calibration factor $N_{D,W}$ in a ^{60}Co beam.

The averages of dose ratio and correction factor ratio by means of plane-parallel chamber for electron beams were 1.007 and 1.020, respectively. In addition, the comparable ratios for the same beam qualities by cylindrical ion chamber were shown to be 0.994 and 0.978. Similar comparisons of dose ratios were made by parallel plate chamber between TRS-381 and TRS-398 and between TRS-277 and 398 which have shown maximum differences of 1.3% and 1.5%, respectively [1].

Beam quality correction factors play an important role both in TRS-398 and TG-51 protocols. Both AAPM TG-51 and IAEA TRS -398 provide sets of theoretically derived k_Q factors for a number of ionization chambers, although IAEA TRS-398 tables provide factors for a larger number of ionization chambers. IAEA has made an effort to include a wide range of ionization chambers used worldwide in TRS-398; details on the calculation procedures which led these k_Q values are given in Appendix B of the IAEA TRS-398 code of practice, along with uncertainty estimates for each component [13]. The k_Q values were based on Bragg-Gray theory with suitable corrections. The combined standard uncertainty in the values for k_Q is 1.0% [17, 18]. There was some practical restriction in the application of these two protocols, such as photon and electron contamination associated with electron and photon therapeutic beams that can arise in area, and set of the chamber in the reference depth.

Previous studies have shown that different simulation codes have been used to calculate the central and off-axis beam specifications [19]. This study showed that the MC simulation can be a reliable method to estimate beam quality factor, at least in conditions like this experiment. In addition, it was concluded that derivation of dosimetric parameters by means of Monte Carlo codes were applicable, and this experiment can be accomplished for other parameters to make the dosimetry simulation more robust and precise for future clinical use [20, 21]. The average difference between simulation and measurement data in beam profile, build-up and linear region of PDD were about -1.62%, -4.17% and 0.38%, respectively for 18MV photon beam, as well as -0.07%, -2.60% and 1.19% for 12 MeV electron beams.

The discrepancies of about 5% have been observed by Ding (2002) in the buildup region for the field with the lead foil between calculated dose with Monte Carlo method and measurement method [22]. Abdel -Rahman *et al.* (2005) and Vassiliev *et al.* (2006) reported that for smaller depths and small field sizes Monte Carlo simulations over estimated the dose in the buildup region while for larger field sizes Monte Carlo simulations underestimated the dose in the buildup region [23, 24]. Hartmann Siantar *et al.* (2001) suggested that this discrepancy was caused by a source of electrons in the Linac head that was not considered for Monte Carlo simulation of the head [25]. On the other hand, a study by Ding and a detailed study with focusing on electron contamination associated with therapeutic 18 MV photon beam reported by Allahverdi *et al.* (2011) showed that this electron contaminant is not due to this discrepancy [22, 26]. The amount of neutron dose in a high energy photon beam reported by Nath *et al.* (1993) has been too small to explain the discrepancies [27]. Further study is needed to find the true cause of this discrepancy of the absorbed doses at the buildup region between Monte Carlo calculation and measurement.

The absorbed dose to water determinations, according to the two protocols was in agreement within experimental uncertainty. The maximum difference in absorbed dose to water determination is obtained for 6 MV and 9MeV. This maximum difference could be related to the use of experimental beam quality correction factors. As stated by Castrillón *et al.* (2009), our results confirmed that the use of different protocols and calibrations traceable to different standard laboratories would cause further differences [5]. The main reason for difference could be related to the use of experimental beam quality correction factors (tables 3 and 4). Two points have to be emphasized here: the first one is that this comparison was performed with a single calibration from Iran SSDL, and the second one is that the best effort has made to simulate the therapy machine as realistic as possible. For these reasons, we found that the results of simulation and experiments show minimal differences. However, authors still believe that there is much more to do for the application of Monte Carlo for exact modeling of certain physical specifications such as energy spectrum of various beams with different qualities [15].

In conclusion it can be said that there is no significant difference between the two dosimetry protocols (IAEA TRS-398 & AAPM TG-51) from the point of view of absolute dosimetry, at least when they are used under the same calibration procedure. The most important point is the data processing and conclusiveness of the parameters used for each dosimetry algorithm. Due to more flexibilities and capabilities of Monte Carlo procedures to estimate of dosimetry parameters, the application of MCNP simulation associated with measurement can be used for more detailed comparison of different dosimetry protocols.

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