

Measurement of neutron dose component in central axis absorbed dose of 18 MV photon beam by TLD600 and TLD700 dosimeters

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ABSTRACT

Background: In spite of clinically useful photon and electron beams, high energy linacs produce secondary particles such as neutrons (photo-neutron production). Neutrons have important roles during treatment with high energy photons in terms of protection and dose escalation. In this project, neutron dose equivalent of 18 MV Varian accelerators is calculated by TLD600 and TLD700.

Methods: For neutron and photon dose discrimination, first TLDs were calibrated versus definite gamma and neutron doses. Gamma calibration was done in two procedures; by standard ⁶⁰Co source and by accelerator 18 MV photon beam. For neutron calibration by ²⁴¹Am-Be source, irradiations were done in several different time intervals. Neutron dose equivalent was calculated in the central axis, on the phantom surface and depths of 1, 2, 3.3, 4, 5 and 6 cm.

Results: No photo-neutron dose was achieved on the phantom surface and depths of 1, 2, 3.3 cm. The maximum photo-neutron dose equivalent was 50 mSv*Gy⁻¹ at the depth of 5 cm.

Conclusion: Photon absorbed dose calculation in central axis has an error of 5%. Neutron dose variation in different depths doesn't show a regular procedure and in it seems to be due to the TLD inaccuracy for neutron dosimetry.

Keywords: Neutron dosimetry, Calibration, Varian accelerator, TLD600, TLD700.

زمینه و هدف: شتابدهنده های خطی با انرژی بالا، علاوه بر باریکه های مفید فوتونی و الکترونی، ذرات ثانویه ای مثل نوترون تولید می کنند. نوترون ها مهمترین ذرات ثانویه تولیدی از نقطه نظر حفاظت و افزایش دز در هنگام درمان با فوتون های با انرژی بالا هستند. در این مطالعه با استفاده از TLD600 و TLD700 دز نوترون حاصل از شتابدهنده واریان با انرژی 18 MV محاسبه شده است.

مواد و روشها: برای جداسازی دز نوترون و فوتون، نخست TLD ها در برابر دزهای مشخص گامایی و نوترونی کالیبره شدند. کالیبراسیون گامایی در دو مرحله با چشمه استاندارد ⁶⁰Co و با شتابدهنده واریان در انرژی 18 MV انجام شد. به منظور کالیبراسیون نوترونی با چشمه ²⁴¹Am-Be، پرتوهای در چند بازه زمانی مختلف انجام گرفت. محاسبه دز فوتونوترون در امتداد محور مرکزی و بر روی سطح فانتوم و در عمق های 1، 2، 3.3، 4، 5 و 6 سانتیمتری انجام شد.

یافته ها: دز فوتونوترون بر روی سطح فانتوم و در عمق های 1، 2 و 3.3 cm برابر با صفر بدست آمد. بیشترین دز فوتونوترون در عمق 5cm و برابر با 50mSv/Gy اندازه گیری شد.

نتیجه گیری: محاسبه دز جذبی فوتون در امتداد محور مرکزی با TLD700 خطایی تا حدود 5% را نشان میدهد. تغییرات دز نوترون نیز در عمق های مختلف روند منظمی را نشان نمیدهد که با توجه به نتایج بدست آمده در دزیمتری فوتون به نظر می رسد به دلیل خطای بالای TLD در دزیمتری نوترون باشد.

واژه های کلیدی: دزیمتری نوترون، کالیبراسیون، شتابدهنده واریان، TLD600، TLD700

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Introduction

Radiotherapy with photon and electron beams still represents the most widely used technique to control and treat tumors. Due to its versatility and flexibility medical linear accelerators, also known as linacs, are widely utilized in radiotherapy where a beam of electrons or photons are applied to eliminate tumor cells.¹

High-energy X-rays offer several advantages over lower energy photons including: lower skin dose, higher depth dose, smaller scattered dose to tissues outside the target volume and less rounded isodose curves. These advantages in physical dose distributions have led to significant improvements in clinical radiotherapy, and high energy linear accelerators are now a standard fixture of radiotherapy clinics.²

Electrons and electromagnetic radiation produced by medical electron accelerators operating at energies above 8 MeV are accompanied by neutrons, which are produced by the giant dipole resonance reactions (($e, e'n$) and (γ, n)) inside the materials constituting the accelerator head structures. Nevertheless, the cross section of the first reaction is two orders of magnitude smaller than that of the second one and may be neglected, except for accelerators used for direct electron irradiation.³

Hence, for linacs operating in X mode, neutrons are produced by photonuclear reactions when the energy of the incident photon is higher than the threshold energy of the (γ, n) reaction. This threshold depends on the atomic number of the target; for high atomic numbers it is around 8 MeV whilst for low atomic numbers the threshold is higher (16 MeV for oxygen, 18 MeV for carbon). Therefore linacs with photon energies in the range of 18–25 MeV can produce undesired fast neutrons, both in the accelerator head and directly in the patient's body, which give a non-negligible contribution to the total dose. However, since peak (γ, n) cross sections for high Z materials are around 50 times higher than for low Z ones (W: 400 mb; C: 8 mb), the accelerator head provides the major contribution. On the other hand, the absorption cross sections of the materials present in the accelerator head are very low for the generated neutron energies. Therefore, neutrons are not shielded by the linac collimators and

reach the patient, contributing an extra dose not taken into account in routine radiotherapy treatments.^{4,5}

The photo-neutron energy spectrum is characterized by an evaporation peak in the range 200–700 KeV and a relatively weak (10% of the integrated intensity) direct-reaction component in the several MeV energy range. The average energy of the resulting primary neutron spectrum is in the range 1–2 MeV. These neutrons are very effective in damaging tissues and their radiation weighting factor ($w_R=20$) is at maximum in the calculations of equivalent dose and effective dose. It is worth noting that, all the neutrons generated in the accelerator head are fast neutrons. Thereby, the total number of generated neutrons is derived from the fast neutron component of the spectra. Thermal and epithermal neutrons appear due to energy losses of fast neutrons by elastic and inelastic collisions inside the treatment room, mainly in the concrete walls and to, a minor extent, in the accelerator head components. A significant number of neutrons are backscattered several times from the walls into the treatment room before being finally absorbed.³⁻⁸

The photo-neutrons are not only effective in damaging tissues, but also can induce activation of some isotopes, mainly those which are abundant inside the treatment room and with large activation cross section like Al, Cu, Mn, W, and Ni. Furthermore, since multi-leaf collimation techniques give a more precise definition of the treatment volume, the gamma dose to the tumor may be raised to improve the effectiveness of the treatment. However, increasing the number of monitor units (MU) in a program of treatment will also increase the secondary neutron dose and if therapy is to be optimized this must be quantified.^{3,5}

The photo-neutron production from the high energy linacs is a radiation protection issue. In order to optimize treatment conditions and avoid unnecessary radiation injury in patient care, the dose from photo-neutron investigation is imperative to provide support for the field of health physics and medical physics to accurately estimate received dose of the patients.⁹

The pulsed time structure of the neutron fields, the very intense photon component and the presence of radiofrequency fields could affect the operation of active dosimeters.¹⁰ Activation foils, bubble detectors and ionization chamber pairs are the basic dosimeters for char-

acterizing neutron beams. The thermo-luminescent (TL) dosimeters¹¹⁻¹³ are also of interest because of their small size and their tissue-equivalence. Since the gamma rays contribute to the TL signal of the dosimeters exposed to a mixed neutron-gamma radiation field, it is difficult to measure the neutron dose with a single dosimeter. As explained in the ICRU report 26,¹⁴ the use of a suitable pair of dosimeters, whose one is more sensitive to neutrons and the other one is more sensitive to photon, is needed to discriminate the contributions of gamma photons and neutrons in the mixed field. The pair of TL dosimeters usually chosen are 6LiF:Mg,Ti (TLD600) and 7LiF:Mg,Ti (TLD700). TLD600 chips are enriched of 6Li which has a high cross-section (about 940 barn) for the reaction with thermal neutrons ($6\text{Li} (n,\alpha)3\text{H}$). Therefore, TLD600 dosimeters are much more sensitive to thermal neutrons than TLD700 dosimeters which are enriched of 7Li. On the other hand, the sensitivity to gamma photons of both types of dosimeters is approximately the same because the interaction with photons depends on the atomic number (not on atomic mass) of the atoms inside the dosimeter.¹¹ Therefore, employment of TL dosimeters pair seems to be a good choice to determine neutron dose in a medical linear accelerator field.

The aim of the present study was to estimate the neutron dose equivalent and photon absorbed dose in central axis by TLD600 and TLD700 for Varian linac operating in 18 MV photon mode.

Materials and Methods

Dosimeters and TL measurements

TLD pairs are commercial 6LiF(TLD600) and 7LiF(TLD700) doped with Mg, Ti from the Harshaw Chemical Co. TLD600 (with 95.6% 6LiF) and TLD700 (with 99.9% 7LiF) are in the shape of chips and dimensions of $3 \times 3 \times 0.9$ mm³. Before each irradiation, all dosimeters were annealed following the producer recommendations. The TLD600 and TLD700 have been heated at 400 °C for 1 h, gradually cooled to room temperature and heated to 100 °C for 2 h. Dosimeters have been analyzed with a model KFKI RMKI TLD reader from Hungary. This instrument gives the TL read-out in count. The time temperature profile used for TLDs in this work is given in *table 1*. The instrument software allows the glow

Table 1. time temperature profile used for TLDs in this work

PREHEAT	
Temp(° C)	100
Time(sec)	25
ACQUISITION	
Max Temp (° C)	300
Time(sec)	20
Rate(° C /sec)	11
ANNEAL	
Temp(° C)	0
Time(sec)	0
COOLING	
Time(sec)	20

curve representation and the determination of the area under the glow curve.

TLD personal calibration

Compensation for material variations due to composition and manufacturing technique between the chips is accomplished using an element correction coefficient (ECC) calibration. Each chip is assigned an ECC, correcting its sensitivity to a definite dose. An ECC is generally determined by irradiating a group of TLDs to a known dose and referencing the response to the average TL value. Calculating the ECC is performed using

Equation 1, where $\langle \text{TLR} \rangle$ is the average read-out of the TLDs, and TLR_j is the read-out of the TLD number j . This ensures that the entire population of TLDs responds almost the same.¹⁶

$$ECC_j = \frac{\langle \text{TLR} \rangle}{\text{TLR}_j} \quad (1)$$

To measure the ECC of each TLD, TLDs were exposed to the same dose of 430 mGy of 60 Co gamma source.

Neutron and gamma dose discrimination by TLD pairs

To discriminate the two components (photon and neutron) of a mixed radiation field, the dosimetric sys-

tem should be constituted of at least two dosimeters, one sensitive to gamma and the other sensitive to neutrons. TLD600 and TLD700 gamma sensitivities are roughly the same, while TLD600 is much more sensitive to thermal neutrons. Consequently, simultaneous use of TLD600 and TLD700 for dosimetry of a mixed field and discriminating the neutron and gamma component is the solution. The response of TLD600 and TLD700 can be related to the gamma dose and neutron dose through the following equations:¹⁴

$$\begin{cases} R_{600}^{n+\gamma} = f_{600}^n D_n + f_{600}^\gamma D_\gamma \\ R_{700}^{n+\gamma} = f_{700}^n D_n + f_{700}^\gamma D_\gamma \end{cases} \quad (2)$$

Where $R_{600}^{n+\gamma}$ is the response of the TLD600 to the mixed field and f_{600}^γ and f_{600}^n are, respectively, the sensitivity factors to photons and neutrons. In analogous way the quantities with 700 subscript are referred to TLD700.

Since neutron sensitivity of TLD600 is about 10^3 times that of TLD700,¹⁷ we assumed $f_{700}^n = 0$. This allows deriving the "thermal neutron signal" with the following simplified equation:

$$R_{600}^n = R_{600}^{n+\gamma} \frac{f_{600}^\gamma}{f_{700}^\gamma} R_{700}^\gamma \quad (3)$$

The expressions of D_n and D_γ can be deduced through these equations:

$$\begin{cases} D_\gamma = \frac{R_{700}^\gamma}{f_{700}^\gamma} \\ D_n = \frac{R_{600}^n}{f_{600}^n} = \frac{R_{600}^{n+\gamma}}{f_{600}^n} - \frac{f_{600}^\gamma}{f_{700}^\gamma f_{600}^n} R_{700}^\gamma \end{cases} \quad (4)$$

To obtain the gamma and neutron doses the user must know the sensitivity factor to gamma and neutron components for each TLD.

To know these sensitivity factors the gamma and neutron calibrations of the TLDs were performed. Gamma calibration was done in two procedures; by standard ^{60}Co source and by linac in 18 MV photon modes. Neutron calibration was also performed by $^{241}\text{Am-Be}$ source.

Gamma calibration by ^{60}Co and linac 18 MV photon beams

The following function as gamma sensitivity curve for TLD600 and TLD700 was used:

$$I_\gamma = f^\gamma D_\gamma$$

Where I_γ is the TL read-out or the TL intensity (area under glow curve) and f^γ is the TLD gamma sensitivity factor. The sensitivity factor is the reverse of the calibration factor, ($f^\gamma = \frac{1}{\sigma_\gamma}$).

The gamma irradiation of TLD chips by ^{60}Co source was performed in a Perspex phantom $30 \times 30 \times 30$ cm³, with a field size of 20×20 cm², at depth of 0.5 cm and the SSD of 80 cm. TLDs were exposed to definite doses of 20.14, 48.9, 100.7, 201.4, 500.6, 799.8 and 1001.24 mGy.

Since TLD response is energy dependent, it is better to do calibration in the same energy of main experiment.¹⁵ Therefore, gamma calibration was also performed by linac 18 MV photon beams and TLD energy correction factor (k_E) was calculated through the following equation:

$$k_E = \frac{\sigma_{Co}}{\sigma_{E=18}} \quad (5)$$

Where σ_{Co} is the calibration factor calculated by ^{60}Co source and $\sigma_{(E=18)}$ is the calibration factor calculated by 18 MV linac photon beams.

To calibrate by 18 MV photon beams, irradiation was done in two procedures; by a thin layer of Cd over TLDs and without it. Cd is used to absorb thermal neutrons. By Cd and irradiating pairs of TLDs to a same dose, the ratio of sensitivity factors is achieved through equations.² TLD700 sensitivity factor is measured separately by its irradiation to several definite doses of 18 MV linac. Conclusively, TLD600 sensitivity factor is also obtained.

The gamma irradiation of TLD chips by linac were performed in a Perspex phantom $30 \times 30 \times 30$ cm³, with a field size of 20×20 cm², at depth of 3.3 cm and the SSD of 100 cm. Pairs of TLDs with a thin layer of Cd over them, were exposed to definite doses of 50, 100 and 150 cGy at depth of d_{max} . TLD700 chips were also separately exposed to definite doses of 50, 100, 150 and 200 cGy at depth of d_{max} .

Neutron calibration by 141Am-Be source

For neutron calibration¹¹ Am-Be source with the activity of 5 Ci was applied. The area under glow curve of the TL signal as a function of thermal neutron dose was studied for all the dosimeters. The neutron average energy is 4.5 MeV. In order to thermalize neutrons, TLDs were placed at the side surface of polyethylene cube with the thickness of 6 cm. The distance of TLDs from the source was chosen 1 m. The dose rate at the point of TLDs was measured 131.4 μSv/h. Neutron irradiations were done in four different time intervals; 21, 44, 64.3 and 111.3 h equivalent to 2.76, 5.78, 8.45 and 14.62 mSv.

We analyzed these experimental data of TLD600 dosimeters through a linear fit with the following function.

$$I_n = f^n D_n$$

Where D_n represents the neutron dose value and f^n is the sensitivity of TLD600 to neutron.

The LINAC set-up

This work was carried out in a Varian 2100CLinac facility. The energy of the photon beam was 18 MV and it was used to irradiate a 30×30×15 cm³ perspex slab phantom. The irradiation area was 20×20 cm² and source to surface distance (SSD) was 100 cm. Linac was set to deliver 300 cGy at the point of maximum dose depth(dmax) (~279 MU), and this was done at a rate of 300 MU/min.

Measurements were performed in central axis by six pairs of TLD600 and TLD700 on the phantom surface and depths of 1, 2, 3.3(dmax), 4, 5 and 6 cm. In order to avoid overlap of TLDs, each point was irradiated separately. *Figure 1* shows the setup of experiment for irradiation of TLDs on the phantom surface.

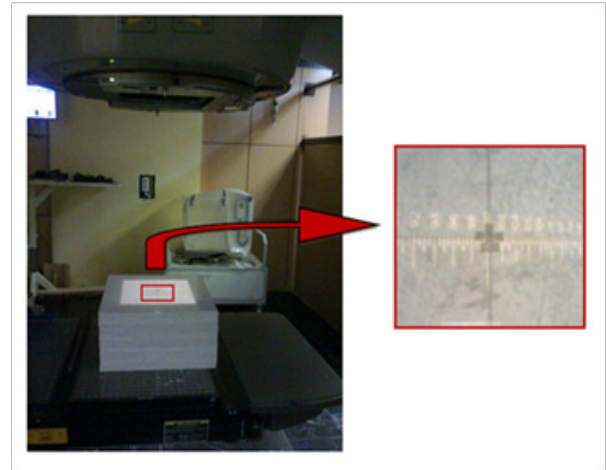


Figure 1: Setup of the experiment for irradiation of TLDs on the phantom surface. (SSD=100 cm and Field=20×20 cm²).

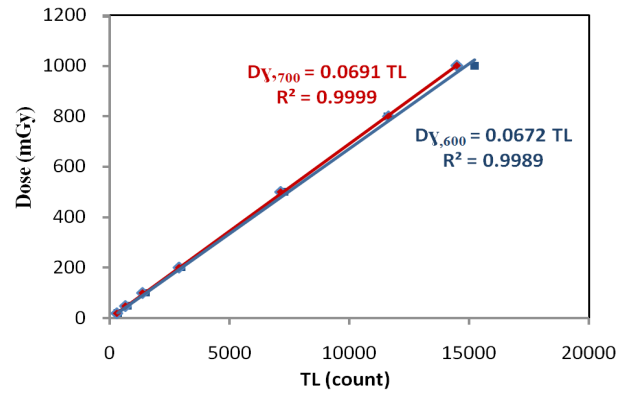


Figure 2- TLD600 and TLD700 gamma calibration curves calculated by 60Co source.

Table 2. TLD600 and TLD700 gamma calibration factors measured by 60Co and linac 18 MV photon beams		
Calibration factor	60Co E=1.25 MeV	Linac E=18 MV
$\sigma_{600}^{\gamma} \left(\frac{mGy}{TL} \right)$	$(67.2 \pm 0.6) \times 10^{-3}$	$(77.8 \pm 3.4) \times 10^{-3}$
$\sigma_{700}^{\gamma} \left(\frac{mGy}{TL} \right)$	$(69.1 \pm 0.2) \times 10^{-3}$	$(89.2 \pm 0.1) \times 10^{-3}$

Results

Figure 2 shows the trends of TL signal of the two dosimeters (TLD600 and TLD700) as a function of 60Co gamma dose.

Table 2 reports the dosimeters' gamma calibration factors measured by 60Co source and 18 MV linac photon beams. As it can be noted from this table, the sensitivities of TLD600 and TLD700 to gamma photons are of

the same order as expected. However, TLD600 gamma sensitivity is a little more than that of TLD700.

Figure 3 shows the TL signal, I_n as a function of thermal neutron dose for the dosimeter TLD600 and the best fit curves are also shown. TLD600 neutron sensitivity

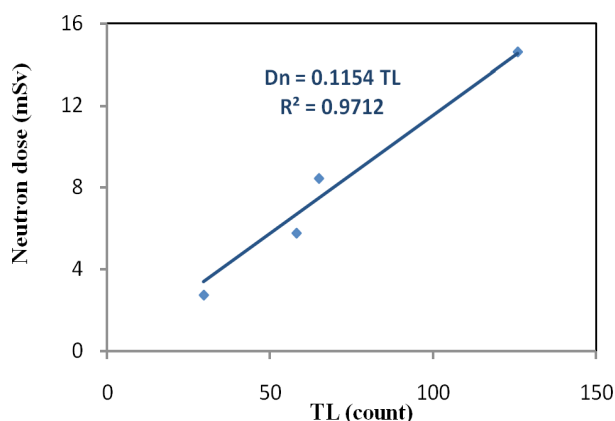


Figure 3- TLD600 neutron calibration curve calculated by Am-Be source.

factor, f_{600}^n , and neutron calibration factor, σ_{600}^n , are calculated as follows:

$$f_{600}^n = 8.6655 \left(\frac{TL}{mSv} \right)$$

$$\sigma_{600}^n = 0.1154 \left(\frac{mSv}{TL} \right)$$

The sensitivity of TLD600 is due to the high capture cross-section of the nuclei of ^6Li (about 940 barns) and to high LET particles (^7Li and alpha particles) released after the neutron capture.

Tables 3 and 4 give the photon absorbed dose and neutron dose equivalent values in central axis calculated by equations.⁵ In table 3, differences are estimated by the results obtained by the ion chamber dosimeter.

From the table 4 can be noticed that D_n is zero in low depths. As the depth increases, D_n takes value and gets its maximum at the depth of 5 cm. It is because of the fact that TLD600 is only sensitive to thermal neutrons and the majority of neutrons on the phantom surface and low depths are fast neutrons. Linac fast neutrons with the average energy of 1-2 MeV are thermalized in depths of 4-5 cm of perspex.

Discussion

Several studies (1-6, 15-19) have been devoted to the evaluation of the photo-neutron dose (or dose equivalent) for patients. However, no similar work has been done by

Table 3. Photon absorbed dose and PDD calculated in the central axis of an 18 MV Varian linac.

Depth (m)	D_γ (mGy)	Differences (%)	PDD	Differences (%)
Phantom surface	1248.3 ± 29.6	4.2	40.1 ± 1.7	6.9
1	2511.9 ± 79.9	0.1	80.8 ± 3.7	2.6
2	3109.0 ± 105.0	4.2	100.0 ± 4.8	1.3
3.3	3079.1 ± 53.9	2.6	99.0 ± 3.8	0.2
4	2850.7 ± 110.3	3.3	91.7 ± 4.7	6.0
5	2783.4 ± 69.3	2.5	89.5 ± 3.8	5.3
6	2676.6 ± 102.1	2.7	86.1 ± 4.4	5.4

Table 4. Neutron dose equivalent calculated in the central axis of an 18 MV Varian linac.

Depth (m)	D_n (mSv.Gy ⁻¹)
Phantom surface	0.0 ± 18.1
1	0.0 ± 41.5
2	0.0 ± 45.9
3.3	0.0 ± 22.1
4	27.3 ± 50.5
5	51.7 ± 50.9
6	41.8 ± 45.5

TLD pairs along the beam axis.

Several authors used Monte Carlo techniques to simulate photon beams from a variety of medical accelerators. Ongaro et al. found maximum equivalent neutron doses of about 2–5 mSv.Gy⁻¹ at the central axis by MCNP4B-GN. They showed that the neutron dose equivalent lies between 1 and 4.8 mSv.Gy⁻¹, depending on accelerator characteristics and distance from the isocenter and As a consequence, the total neutron dose equivalent evaluated for a complete therapeutic treatment of 60 Gy photon dose lies between 60 mSv and 288 mSv.¹⁹

Martinez et al. calculated the neutron equivalent dose in tissue for various linacs (Varian Clinac 2100C, Elekta Inor, Elekta SL25 and Siemens Mevatron KDS) operating at energies between 15 and 20 MV, using the Monte Carlo

code MCNPX (v. 2.5). In *figure 4* neutron dose equivalent as a function of the depth in the phantom, along the beam axis, for the Varian Clinac is given.¹⁶

As it can be seen from this figure, neutron dose equivalent decreases by increasing depth in phantom. In this study, neutron dose equivalent is calculated in general and there is no distinction between thermal and fast neutrons. But in our study only the thermal neutron dose equivalent is measured which has no value on the phantom surface.

As it can be seen, our results are about ten times more than data given in articles.^{16, 19} Since the errors in determining the photon absorbed doses are up to 7% (table 3), the neutron uncertainty seems to be due to the TLD inaccuracy. So it is recommended to use TLDs for measurements of “off axis”.

Conclusions

The neutron dose equivalent from photo-neutrons to patients in a typical linac treatment facility is not negligible and neutron field evaluation is therefore necessary to optimise the treatment. In this study, the photo-neutron contamination arising from a medical linear accelerator has been calculated in the central axis by TLD600 and TLD700 dosimeters. The comparison of results with other studies show that TLD600 and TLD700 pairs do not seem to be a reliable tool in the study of doses to patients from emitted photo-neutrons in central axis and a very accurate knowledge of their photon sensitivity is needed to correctly derive the “neutron signal”.

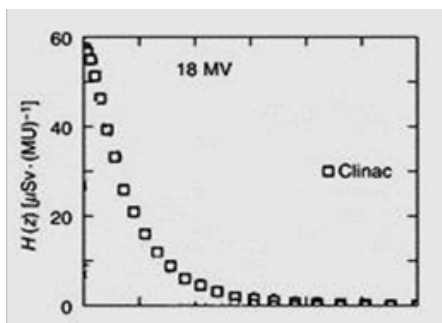


Figure 4- Neutron dose equivalent as a function of the depth in the phantom z , along the beam axis, for the Varian Clinac according to the study of Martinez et al.¹⁶

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