Neutron dose measurements of Varian and Elekta linacs by TLD600 and TLD700 dosimeters and comparison with MCNP calculations

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ABSTRACT

High-energy linacs produce secondary particles such as neutrons (photoneutron production). The neutrons have the important role during treatment with high energy photons in terms of protection and dose escalation. In this work, neutron dose equivalents of 18 MV Varian and Elekta accelerators are measured by thermoluminescent dosimeter (TLD) 600 and TLD700 detectors and compared with the Monte Carlo calculations. For neutron and photon dose discrimination, first TLDs were calibrated separately by gamma and neutron doses. Gamma calibration was carried out in two procedures; by standard 60Co source and by 18 MV linac photon beam. For neutron calibration by 241Am-Be source, irradiations were performed in several different time intervals. The Varian and Elekta linac heads and the phantom were simulated by the MCNPX code (v. 2.5). 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. The maximum photoneutron dose equivalents which calculated by the MCNPX code were 7.06 and 2.37 mSv.Gy⁻¹ for Varian and Elekta accelerators, respectively, in comparison with 50 and 44 mSv.Gy⁻¹ achieved by TLDs. All the results showed more photoneutron production in Varian accelerator compared to Elekta. According to the results, it seems that TLD600 and TLD700 pairs are not suitable dosimeters for neutron dosimetry inside the linac field due to high photon flux, while MCNPX code is an appropriate alternative for studying photoneutron production.

Key words: Elekta, MCNPX code, neutron dosimetry, TLD600, TLD700 varian

Introduction

Radiotherapy with high-energy photon beams represents the most widely used technique to treat tumors. Accordingly, medical linear accelerators, also known as linacs, are greatly utilized.

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In spite of clinically useful photon and electron beams, high energy linacs operating at energies higher than 8 MeV, produce secondary particles such as neutrons because of their high range in media and the high LET of their byproducts. Photoneutrons are produced by the giant dipole resonance reactions, (γ, n), when the incident photon energy is above the threshold energy of the (γ, n) reaction. This threshold depends on the atomic number of the target and is around 8 MeV for high atomic numbers (7.42 MeV for tungsten).[1-3]

Neutrons are generated in the accelerator head (target, collimators, flattening filter, and shields), treatment room, and directly in the patient’s body. However, since cross sections for high Z materials are around 50 times higher than for low Z, photoneutron production is mainly due to (γ, n) reactions in the accelerator head. Moreover, the high Z materials present in the accelerator head have low neutron absorption cross-sections 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 radiotherapy treatments.[1-4]
It is difficult to measure photoneutron dose inside the treatment field due to very intense gamma irradiation. Several authors used passive detectors such as activation gold foils, bubble detectors, CR-39 nuclear track detectors and thermoluminescent dosimeters (TLDs) to study photoneutron production. Few studies have been devoted to the evaluation of the photoneutron dose in different linacs: Followill et al. measured the neutron fluence at the patient plane for various linacs using activation gold foils. Howell et al. used the same technique, measured neutron spectra, neutron fluences, and ambient dose equivalents for various linacs.

The MCNP simulation has been used to study neutron production due to different problems in neutron dosimetry. Ongaro et al. evaluated the neutron production in the high Z components of a Siemens Mevatron linac. Chibani and Ma studied the field size effects on neutron in different linacs: Followill et al. measured the neutron fluence at the patient plane for various linacs using activation gold foils. Howell et al. used the same technique, measured neutron spectra, neutron fluences, and ambient dose equivalents for various linacs.

In this work, thermal neutrons in Varian and Elekta linacs have been measured using TLD600 and TLD700 dosimeters and the Monte Carlo code MCNPX (v. 2.5). The study follows two points. First, Varian and Elekta linacs have been investigated with the same methodology, in order to have a meaningful comparison. Secondly, the results obtained by TLDs and the MCNP code have been compared.

**Materials and Methods**

**Experimental method**

As described in the International Commission on Radiation Units and Measurement report 26, the dosimetry in a neutron-gamma mixed field like the Linac field needs at least two dosimeters, one sensitive to gamma and the other sensitive to neutrons. The dosimeters applied in this work are TLD600 (LiF: Mg, Ti) and TLD700 (LiF: Mg, Ti). TLD600 has a high thermal neutron capture cross-section whilst TLD600 is much more sensitive to thermal neutrons.

The response of TLD600 and TLD700 to a neutron-gamma mixed field is given through the following equation:

\[ R^{\gamma}_{\text{TL}} = R^{\gamma}_{\text{TL600}} + \frac{\alpha^{\gamma}_{\text{TL600}}}{\alpha^{\gamma}_{\text{TL700}} } R^{\gamma}_{\text{TL700}} \]  

Where \( R^{\gamma}_{\text{TL600}} \) and \( R^{\gamma}_{\text{TL700}} \) are the TLD600 and TLD700 total responses to the mixed field, respectively; \( \alpha^{\gamma}_{\text{TL600}} \) and \( \alpha^{\gamma}_{\text{TL700}} \) are TLD600 and TLD700 gamma calibration factors, respectively; and \( R^{\gamma}_{\text{TL700}} \) is the neutron contribution.

Since neutron sensitivity of TLD600 is about 10\(^3\) times that of TLD700, no neutron sensitivity was assumed for TLD700.

The gamma and neutron doses, \( D_{\gamma} \) and \( D_n \), in a mixed radiation field can be deduced through these equations:

\[
\begin{align*}
D_{\gamma} &= \alpha^{\gamma}_{\text{TL600}} R^{\gamma}_{\text{TL600}} \\
D_n &= \alpha^{\gamma}_{\text{TL600}} R^{\gamma}_{\text{TL600}} \alpha^{\gamma}_{\text{TL700}} R^{\gamma}_{\text{TL700}} \\
&= \frac{\alpha^{\gamma}_{\text{TL600}}}{\alpha^{\gamma}_{\text{TL700}} } R^{\gamma}_{\text{TL700}}
\end{align*}
\]

To obtain \( D_{\gamma} \) and \( D_n \), the user must know the gamma and neutron calibration factors. To determine these factors the gamma and neutron calibrations of the TLDs were performed.

All TLDs were read out employing a KFKI RMKI reader (KFKI Research Institute of The Hungarian Academy of Sciences, Budapest, Hungary). The read-out cycle included 100°C 25 s (preheat), 11°C s\(^{-1}\) linear ramp to 300°C for 12 s, and the unit of read-out was counted.

**TLDs gamma and neutron calibration**

The following function was used as the gamma calibration curve for TLD pairs:

\[ D_{\gamma} = \alpha^{\gamma} I_{\gamma} \]  

Where \( I_{\gamma} \) is the TL read-out or the TL intensity (area under glow curve) and \( \alpha^{\gamma} \) is the gamma calibration factor.

The gamma irradiation of TLD chips by 60Co source was performed in a Perspex phantom of \( 30 \times 30 \times 30 \) cm\(^3\), with a field size of \( 20 \times 20 \) cm\(^2\), at depth of 0.5 cm, and the source to surface distance (SSD) of 50 cm. TLDs were exposed to definite doses of 20, 50, 101, 201, 501, 800, and 1001 mGy.

Since TLD response is energy dependent, it is better to do calibration in the same energy to experiment. 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:

\[ K_E = \frac{\sigma_{\text{Co}}}{\sigma_{\text{60Co}}} \]
Where $\sigma_{E=18}$ is the calibration factor calculated by 18 MeV linac photon beam and $\sigma_{Co}$ is the calibration factor calculated by $^{60}$Co source.

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

The gamma irradiation of TLD chips by linac were performed in a Perspex phantom with the dimensions of $30 \times 30 \times 30$ cm$^3$, a field size of $20 \times 20$ cm$^2$, at depth of 3.3 cm (maximum dose point), and the SSD of 100 cm. Pairs of TLDs with a 2 mm thin layer of Cd which was in between the incoming beam and TLDs, were exposed to definite doses of 50, 100, and 150 cGy at depth of dmax. TLD700 chips were also separately exposed to definite doses of 50, 100, 150, and 200 cGy at depth of dmax.

For neutron calibration, $^{24}$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 $\mu$Sv.h$^{-1}$. Neutron irradiations were done in four different time intervals; 21, 44, 64, and 111 h equal to 3, 6, 8, and 15 mSv, respectively.

Since the Am-Be emission is accompanied with photon radiation, the TLD600 signal is due to both neutrons and photons and the gamma component must be subtracted from the total TLD600 signal. As mentioned, TLD700 neutron sensitivity was presumed zero. Consequently, the gamma component provided by the TLD700 dosimeters in the mixed field was subtracted and the neutron calibration curve for TLD600 dosimeters was estimated as follows:

$$D_n = \alpha^nI_n \quad \ldots \ldots (5)$$

Where $I_n$ represents the TL intensity due to thermal neutrons and is the neutron calibration factor.

The linac setup

The medical linear accelerators investigated in this study were Varian Clinac 2100C and Elekta Precise. The energy of the photon beam was 18 MV and it was collimated to an area of $20 \times 20$ cm$^2$ at distance of 100 cm. Linac was set to deliver 300 cGy at the point of maximum dose depth, dmax, with dose rate of 300 MU/min.

Measurements were performed in central axis by six pairs of TLD600 and TLD700 manufactured by KFKI Research Institute on the phantom surface and depths of 1, 2, 3.3 (d$_{max}$), 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 for two linacs.

**Monte Carlo simulation**

Neutrons are produced by photonuclear reactions in the high Z materials of the linac head. Therefore, to estimate the neutron production using Monte Carlo calculations, a detailed geometry of the linac head (target, primary and secondary collimators, flattening filters, etc.) is needed. A big sphere ($R = 2.5$ m) around the machine which was filled by air also simulated.

The geometries were modeled according to the manufacturers’ details. Electron beam with dimension of 5 mm radius, impinges the target. We assumed an electron point source beam in downward direction, Gaussian energy distribution according to manufacturer remarks. In both cases, slab phantom (water equivalent materials with the dimensions of $30 \times 30 \times 30$ cm$^3$) at 100 cm from the source was simulated. In order to reduce run time, energy cutoff variance reduction method was applied for photons and electrons when the mode was electron-photoneutron, because the threshold of neutron production is less than 8 MeV the energy cutoff was increased to 7 MeV for both electron and photon. Simulations were performed using the MCNPX code (v. 2.5). The neutron flux was determined in the phantom as a function of the depth, using the F4 tally. The sizes of the cells used for simulation was 0.5 $\times$ 0.5 mm and depth of 2 mm with cylindrical shape. For comparison between experimental and simulation results, flux to equivalent dose conversion factor were used in the range of thermal neutron energies. Figures 2 and 3 illustrate the geometries used for the simulations. The composition and densities of the linac head components are given in Table 1.

For both linacs, the neutron flux was estimated in the phantom along the central axis as a function of the...
depth, using the F4 tally. In order to have the neutron dose equivalent values, flux to equivalent dose conversion factors in the range of thermal neutron energies were used according to NCRP 38 Reports. The number of histories run in all cases was $2 \times 10^9$, which assures that the estimated statistical error is <2%.

**Results**

**Measurement results**

The TL response of the two dosimeters (TLD600 and TLD700) versus 60Co gamma dose is shown in Figure 3. Figure 4 shows the TL signal, $I_a$, as a function of thermal neutron dose for the TLD600 dosimeter. Table 2 presents the gamma and neutron calibration factors of the dosimeters. The standard deviations, $s$, of the calculated quantities are also given. As it can be considered from this table, the gamma sensitivity factors of the two dosimeters are of the same order of magnitude. Nevertheless, the gamma sensitivity of TLD600 is a bit more than TLD700. The neutron sensitivity of TLD600 is higher than TLD700 because of the large neutron capture cross-section of the nuclei of 6Li in this dosimeter.

Table 3 gives the photon-absorbed dose and neutron dose equivalent values in central axis calculated by equations. The results are normalized to the dose of 1 Gy at the point of maximum dose depth, $d_{max}$. The differences in gamma doses, $D_\gamma$, are estimated by the values obtained by the measurement of 0.6 cc ion chamber dosimeter. These results show fairly a good agreement.

From the Table 3 it can be noticed that neutron equivalent dose, $H_n$, is nearly zero at build up region. As the depth increases, $H_n$ takes value and gets its maximum at the depths of 4 and 5 cm for Elekta and Varian linacs, respectively. It is because of the fact that TLD600 is only sensitive to thermal neutrons and the majority of neutrons on the phantom surface and build up region are fast neutrons. Linac fast neutrons with the average energy of 1-2 MeV are thermalized at depths of 4-5 cm of perspex.

**MCNP results**

Figure 5 shows the benchmarked Monte Carlo data with experimental percentage depth dose measurements. The measured and calculated doses are in good agreement (within 2%/2 mm). The maximum difference is less than 2% which validates the MCNPX simulations of the calculations.

### Table 1: The materials of the linac head components considered in this work

| Linac head components | Varian Clinac 2100C | Elekta Precise |
|-----------------------|---------------------|----------------|
| Target                | W                   | W/Re           |
| Percentage            | 100                 | 90/10          |
| Density (g cm\(^{-3}\)) | 19.3               | 19.4           |
| Target cover          | Cu                  | Cu             |
| Percentage            | 100                 | 100            |
| Density (g cm\(^{-3}\)) | 8.96               | 8.96           |
| Primary collimator    | W                   | W/Ni/Fe        |
| Percentage            | 100                 | 95/3.75/1.25   |
| Density (g cm\(^{-3}\)) | 19.3               | 18.0           |
| Flattening filter     | Ta/Fe               | C/Si/Ni/Cr/Mn/Fe |
| Percentage            | -                   | 0.15/0.85/9/18/2/70 |
| Density (g cm\(^{-3}\)) | 16.65/7.874         | 7.8            |
| Secondary collimator  | W                   | Pb/Sb/W        |
| Percentage            | 100                 | -              |
| Density (g cm\(^{-3}\)) | 19.3               | 18             |

### Table 2: Gamma and neutron calibration factors of TLD600 and TLD700 dosimeters

| Dosimeter | $a_\gamma \pm \sigma$ (mgY counts) | $a_n \pm \sigma$ (msv counts) |
|-----------|-----------------------------------|-------------------------------|
| 60Co (1.25 MeV) | (67.2±0.6)×10\(^{-3}\) | (77.8±3.4)×10\(^{-3}\) |
| Linac (18 MV)  | (115.4±5.6)×10\(^{-3}\) |
| TLD600   | (69.1±0.2)×10\(^{-3}\) | (89.2±0.1)×10\(^{-3}\) |
| TLD700   | -                               | -                             |

TLD: Thermoluminescent dosimeter

Figure 2: MCNP simulation for the Varian Clinac 2100C and Elekta Precise linacs

Figure 3: TLD600 and TLD700 gamma calibration curves calculated by 60Co source. TL = Thermoluminescent
The neutron dose equivalents, \( H_n \), are calculated relative to the number of initial electrons needed to generate an absorbed dose of 1 Gy due to photons in the maximum. In Table 2, the values of \( D_{p}^{\text{max}} \) were included.

Figure 6 shows the neutron dose equivalent values along the beam axis, as a function of the depth in the phantom for the two linacs. Therein, squares correspond to Varian Clinac and circles to Elekta Precise. The results for the Varian accelerator are considerably larger than those found for the Elekta. As it can be noticed from Figure 6, the neutron dose equivalents at the entrance of the phantom (in the first few depth centimeters) grow up to the depths of 4 and 4.5 cm for Varian and Elekta linacs, respectively and then decreases. At depths over 20 cm these values are inconsiderable and can be ignored. Table 4 includes the maximum photoneutron dose equivalent values, \( H_n^{\text{max}} \), and the depth at which this maximum is reached, \( d_{\text{max}} \). The maximum photoneutron dose equivalent for Varian is about three times higher than that of Elekta (7.06 mSv.Gy\(^{-1}\) versus 2.37). This larger production is mainly related to the materials and the geometry of the linac head configuration as well as the accelerating potential of the incident electrons impinging the target.

**Discussion**

The comparison between the measured and calculated neutron dose equivalent values, \( H_n \), at corresponding measuring depths is given in Table 5. As it can be noticed there is a significant difference between the results achieved by TLDs and those obtained by MCNPX code; the measured data are much more than calculated ones excluding the zero values in the first of depth centimeters.

Several studies have been devoted to the evaluation of the photoneutron dose produced by the high energy linac. \(^{1-12,17-22}\)

**Table 3: Photon absorbed dose and neutron equivalent dose values measured at the central axis of an 18 MV Varian and Elekta linacs. The results are normalized to the dose of 1 Gy at the point of maximum dose depth, \( d_{\text{max}} \)**

| Depth (cm) | Varian \( D_\gamma \) (mGy) | \*Differences (%) | \( H_n \) (mSv.Gy\(^{-1}\)) | Elekta \( D_\gamma \) (mGy) | \*Differences (%) | \( H_n \) (mSv.Gy\(^{-1}\)) |
|-----------|-----------------|------------------|-----------------|-----------------|------------------|-----------------|
| Phantom surface | 416.1±9.8 | 4.2 | 0±18.1 | 442.7±13.5 | 5.8 | 0±26.4 |
| 1 | 837.1±26.6 | 0.1 | 0±41.5 | 868.9±12.8 | 4.7 | 0±40.8 |
| 2 | 1036.4±35.0 | 4.2 | 0±46.0 | 937.8±22.6 | 6.2 | 0±25.4 |
| 3.3 | 1026.4±18.0 | 2.6 | 0±22.1 | 939.4±16.2 | 5.2 | 14.6±53.9 |
| 4 | 950.2±36.8 | 3.3 | 27.3±50.5 | 942.2±14.2 | 2.6 | 44.4±55.8 |
| 5 | 927.8±23.1 | 2.5 | 51.7±50.8 | 909.2±21.7 | 4 | 42.2±43.5 |
| 6 | 892.2±34.0 | 2.7 | 41.8±45.5 | 880.4±15.9 | 3.3 | 36.6±33.0 |

\*The differences in \( D_\gamma \) values are estimated by the results obtained by the by the measurement of 0.6 cc ion chamber dosimeter
However, no similar work has been done by TLD pairs in the central axis. According to the results it seems that TLD600 and TLD700 dosimeters are not a reliable tool in the study of doses to patients from emitted photoneutrons along the beam axis. In all the measurements, the neutron dose uncertainty is very great because the contribution due to neutrons in the used mixed field is however much lower than the contribution due to photons.

As mentioned many studies have been carried out to analyze the linac produced photoneutrons, but most have evaluated only one type of linac and the methods used have differed widely. Only few studies have investigated the photon neutron production in different linacs. In the studies performed by Followill et al.,[17] and Howell et al.,[18] neutron fluence, spectra and ambient dose equivalent were evaluated at the patient plane using activation gold foils. Martínez-Ovalle et al.,[22] calculated neutron absorbed dose, fluence, spectra, and dose equivalent along the central axis in tissue by MCNPX code for various linacs. All these studies reported the significantly larger photoneutron production in Varian linacs compared to other commercially available ones (Elekta and Siemens) in the same nominal energy. The results obtained in this work [Figure 6] also represents that photoneutron production in Varian linac is much more than Elekta which is in consistent with the published data. This is mainly due to the fact that despite the same nominal energy in these machines, different manufacturers employ different strategies in the design of the accelerator.

The number of photoneutrons originated is particularly dependent on the photon spectra and the materials forming the linac head components (the (γ, n) reaction cross-section varies with the two following factors: Gamma energy and the target atomic number). Beams with higher energies will result in more (γ, n) reaction and ultimately more neutrons will be produced. The beam energy is defined according to the maximum accelerating potential of the electrons striking the target. For a given specified energy, the maximum accelerating potential varies between different manufacturers, for example, a nominal 18 MV beam has the maximum photon energy of 18.75 or 15.3 MeV in Varian Clinac and Elekta precise, respectively. The fact that the electron energies tuned for Varian Clinac is larger than that for the Elekta contributes to the observed neutron production. Even though the energy of the initial electrons plays a prominent role in neutron dose, the materials used in the linac head are also important. Materials with higher atomic number will cause in more photoneutron production. As it can be seen from Table 1, the flattening filter, primary and secondary collimators in Elekta Precise are made of lighter materials than those of the Varian Clinac. However, the target in the case of the Varian Clinac is made of W and that of the Elekta Precise has a mixture of W and other heavier material, Re.

According to the results of this work [Figure 6], the neutron dose equivalents at the entrance of the phantom grow up to the depths of 4 and 4.5 cm for Varian and Elekta linacs,
respectively and then decreases. In the study performed by Martinez-Ovalle et al.,\cite{22} the neutron dose equivalent, calculated along the beam axis, has the maximum at the entrance of the phantom and reduces exponentially with the depth. This reduction is related to the cross-section for elastic neutron-hydrogen collisions at the maximum energies present in the neutron spectra. The results obtained by Chibani and Ma\cite{26} in neutron absorbed dose showed the similar trend. Nevertheless, their reduction rate is much lower than that of Martinez-Ovalle et al.'s. Chibani and Ma calculated the neutron production in both the linac head and the phantom and therefore the neutron dose reduced with the lower rate. It is important to note that, in the studies carried out by Martinez-Ovalle et al., and Chibani and Ma, all neutron energy ranges were included and there was no distinction between thermal and fast neutrons. However, in our study only the neutron dose equivalent from thermal neutrons \(E < 0.01 \text{ MeV}\) was considered in order to be compared with the TLDs measured data.

Neutrons originated from linac head have average energies between 1 and 1.5 MeV.\cite{22} These fast neutrons undergo mainly elastic collisions with hydrogen. They lose energy until they become thermal at depths of 4-4.5 cm in the phantom and so the neutron dose equivalent reaches the maximum. At this point, thermal neutron capture becomes dominant and the neutron dose reduces with depth.

Despite the fact that the results depend on the linac type and the measuring setup (most data available are given in the isocenter), we can compare our results with those presented in the literature. The Martinez-Ovalle et al.'s study showed the maximum neutron dose equivalents of 60 and 28 \(\mu\text{Sv.MU}^{-1}\) for 18 MV Varian 2100C and Elekta SL25, respectively, as against our 75.9 and 25.6 \(\mu\text{Sv.MU}^{-1}\) between 1 and 1.5 MeV.\cite{22} These fast neutrons undergo neutrons \(E < 0.01 \text{ MeV}\) was considered in order to be compared with the TLDs measured data.

Saeed et al.,\cite{27} calculated the neutron dose equivalent of the 18 MV Varian 2100C by the Geant4 code about 4.4 mSv.Gy\(^{-1}\) at the isocenter; whereas, the values found by Fernández et al.,\cite{6} were 6 mSv.Gy\(^{-1}\) using activation gold foils. These results show a reasonable agreement with what we found in this study \((6.07 \text{ mSv.Gy}^{-1})\).

**Conclusion**

In this study the photoneutron contamination arising from the 18 MV Varian Clinac 2100C and Elekta Precise has been estimated using TLD600 and TLD700 pairs and the MCNPX code. The results represent the larger photoneutron production in Varian linac compared to Elekta due to the differences in the linac head configuration as well as the accelerating potential of the incident electrons impinging the target. According to the results, TLD600 and TLD700 pairs do not seem to be a reliable tool in the study of doses to patients from emitted photoneutrons in central axis, while the comparison of the MCNPX code results with other published data showed a coherent agreement, confirming the MCNPX code to be a valuable tool for studying photoneutron production along the beam axis.

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