THE NEUTRON DOSE EQUIVALENT AROUND HIGH ENERGY MEDICAL ELECTRON LINEAR ACCELERATORS

by

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The measurement of neutron dose equivalent was made in four dual energy linear accelerator rooms. Two of the rooms were reconstructed after decommissioning of ^{60}Co units, so the main limitation was the space. The measurements were performed by a nuclear track etched detectors LR-115 associated with the converter (radiator) that consist of ^{10}B and with the active neutron detector Thermo BIOREM FHT 742. The detectors were set at several locations to evaluate the neutron ambient dose equivalent and/or neutron dose rate to which medical personnel could be exposed. Also, the neutron dose dependence on collimator aperture was analyzed.
The obtained neutron dose rates outside the accelerator rooms were several times smaller than the neutron dose rates inside the accelerator rooms. Nevertheless, the measured neutron dose equivalent was not negligible from the aspect of the personal dosimetry with almost 2 mSv a year per person in the areas occupied by staff (conservative estimation). In rooms with 15 MV accelerators, the neutron exposure to the personnel was significantly lower than in the rooms having 18 MV accelerators installed. It was even more pronounced in the room reconstructed after the ^{60}Co decommissioning. This study confirms that shielding from the neutron radiation should be considered when building vaults for high energy linear accelerators, especially when the space constraints exist.

Key words: radiotherapy, electron linear accelerator, neutron equivalent dose

INTRODUCTION

At present, a high energy electron linear accelerators producing photons of energies higher than 10 MeV have a wide use in radiation therapy. However, in those beams, fast neutrons could be generated which results in the undesired contamination of the therapeutic beams. The high energy photons can interact with the atomic nucleus of a high-Z material, of which the target and the head of the accelerator consist, and lead to the neutron ejection. The neutrons are produced in a giant dipole resonance reaction between the photon beam and the accelerator's head material (led, tungsten) [1-3]. In this reaction, an isotropic flux of neutrons is produced, dominated by the neutrons with energies between 700 keV and 1 MeV. This effect becomes more pronounced when high numbers of monitor units (MU) are used, as in the intensity modulated radiotherapy (IMRT) [4]. Herein, it is important to determine the full radiation field correctly, in order to evaluate the exposure of patients and medical personnel.

In Croatia, 9 linear accelerators were installed during the last 5 years. Thus, the units for three linear accelerator buildings of decommissioned ^{60}Co were reconstructed. Due to the differences in size of those machines and its auxiliary systems the main limitation of the reconstruction was space. The objective of this work was to assess the neutron dose in the vicinity of 4 accelerators, 2 of which are installed in the place of decommissioned ^{60}Co units. The measurements of neutron doses during this study showed a possible rise of neutron doses when neutron flux is not considered in shielding calculations. This led to the afterward reconstruction of one of the vaults. The measurement results during all stages of the reconstruction are also presented in this work. The second objective of this work was to assess the impact of collimation to the neutron dose.

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MATERIALS AND METHODS

In this work a passive neutron dosimeter was used for measuring the neutron dose equivalent around high energy medical electron linear accelerators. It consists of a solid state nuclear track-etched detector (SSNTD) LR 115 and a boron foil that contains ^{10}B isotope (both manufactured by Kodak Pathe, France) used as a converter. The converter is necessary in order to create the secondary, charged particle that can be detected on the detector surface. So, the neutrons are detected indirectly, through $^{10}\mathrm{B}(n, \alpha)\,^{7}\mathrm{Li}$ reaction. The working principle and calibration of the detector is explained in detail elsewhere [2]. At calibration, the response of the neutron dosimeter for thermal neutrons was calculated as ratio of counted net track density of detector, D_{t}, and known neutron fluence, f, to which the detector was exposed

$$r_{\mathrm{t}} \quad \frac{D_{\mathrm{t}}}{f}(7.930 \quad 0.071)10^{\;4}\ \text{track per neutron} \qquad (1)$$

Considering the energy dependence of total cross-section for neutrons on boron, $\sigma \ E$ [5], one can determine the respective mean cross-section $\sigma_{\mathrm{t}}=1000$ barn for the energy region of the thermal neutrons used at calibration. To resolve the energy dependence of our dosimeters we have used the neutron spectra measured for the same accelerators and beams [3]. We supposed the similar, softened neutron spectrum in all measuring locations.

The total cross-section for the region of interest marked as σ_1 was determined by the integration of the curve $\sigma \ E$ in the energy region: $10^{-3} < E_1 < 10$ eV. The result of this integration gave us a total cross section of $\sigma_1 = 4671.1$ barn.

Following the described procedure, it is possible to determine the neutron detector response for any other interesting energy class of neutrons (if the spectrum is known) as follows

$$\frac{\sigma_{\mathrm{t}}}{\sigma_1} \quad \frac{r_{\mathrm{t}}}{r_1} \quad r_1 \quad \frac{r_{\mathrm{t}}\sigma_1}{\sigma_{\mathrm{t}}} \qquad (2)$$

where r_{t} is the thermal neutron detector response determined during the calibration (1). In our calculation r_1 is the detector response for the neutron energy region E_1.

For the measured detector density D_1, the respective neutron fluence from eq. (1) was $f_1 = D_1/r_1$.

When the neutron fluence is known, a conversion coefficient k from neutron fluence to dose equivalent, in dependence of the neutron energy, gives an ambient dose equivalent as follows: $H_1 = k_1 f_1$. Having considered a great energy dependence of the conversion coefficient for the neutron radiation, $k(E)$, [5], we calculated the effective conversion coefficient k_1 for the same energy region described as above. As a result of that integration a value $k_1 = 137.74$ pSv cm^2 was obtained.

The results are presented as neutron dose equivalent per accelerator photon dose at isocenter, [μSvGy^{-1}].

To check the measurements done by a passive dosimeter as described above, we used a Thermo Scientific FHT 752 BIOREM. The Thermo Scientific FHT 752 BIOREM is a commercial neutron dose rate meter for stationary and portable use, especially suited for environmental measurements. It employs a $\mathrm{BF_3}$ proportional counter placed in a cylindrical moderator containing polyethylene and boron carbide. The detector has strong energy dependence and it is already described in the literature [6, 7].

The neutron dose measurements produced by high energy photon beams were performed for four Siemens linear accelerators – the Mevatron MD2 (15 MV, accelerator I) and the Oncor Expression (18 MV, accelerator II) – at the University Hospital Osijek as well as the Oncor Impression (15 MV, accelerator III) and the Oncor Expression (18 MV, accelerator IV) installed at the radiotherapy department of the University Hospital Rijeka. All machines are dual energy photon beam linear accelerators. Nevertheless, due to the negligible cross-sections for neutron productions in low energy photon beam (specified as the 6 MV beam with mean energy approx. 2 MeV), the neutron doses were measured only in high energy beams (specified as the 15 MV and 18 MV beams with mean energies approx. 5 MeV and 6 MeV, respectively). The neutron source strengths (Q) determined as neutron fluence per photon Gy is 3 to 5 times larger for the 18 MV accelerators than the 15 MV [8].

The design of accelerator vaults includes a main treatment room with a maze leading to the room entrance. The maze length allows the usage of a much lighter entrance door [9]. Both hospitals have one 15 MV and one 18 MV beam accelerator, but there are large differences in the construction of the buildings, in which the accelerators are placed. Namely, in both hospitals, only one accelerator vault was built for the linear accelerator, the other vault was rebuilt due to the exchange of decommissioned cobalt unit with accelerator. The lack of space was characteristic for both rebuilt vaults. Therefore, the mazes are very short and the plates of steel in combination with the concrete were used for shielding, making the neutron flux more pronounced. It is important to notice that at the University hospital Osijek, the ^{60}Co unit was replaced by the accelerator with high energy beam of 18 MV, and at the University hospital Rijeka by accelerator with the 15 MV beam. Figures 1 and 2 show the accelerator vaults built at the University hospital Osijek and Rijeka, respectively.

The measurements were performed at four positions: at the operator's console (A), on both sides of the vault door approximately 150 cm above the floor (B – outside the vault, C – inside the vault) and on the outside wall of the accelerators' vaults at the central axis

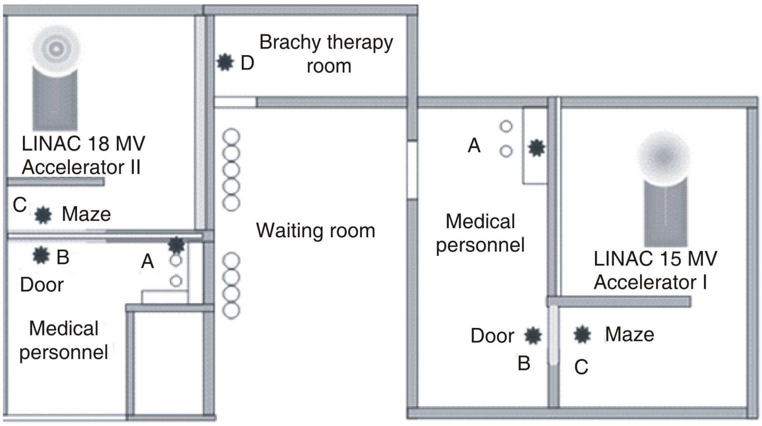

Figure 1. Scheme of two vaults at University hospital centre of Osijek. The 18 MV accelerator is positioned in a smaller vault instead of decommissioned ^{60}Co unit. Measuring points are presented for both accelerators. For 15 MV accelerator the measuring locations A and D are the same

✱ Measuring locations

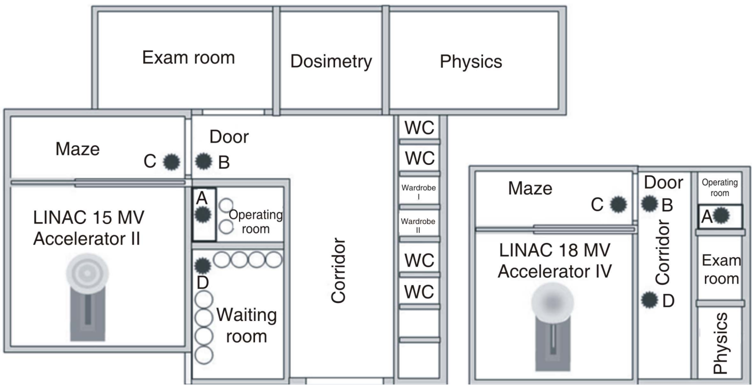

Figure 2. Scheme of two vaults at University hospital centre of Rijeka. The 15 MV accelerator is positioned in a smaller vault instead of decommissioned ^{60}Co unit. Measuring points are presented for both accelerators

of the beam (D). For a better understanding of the obtained results, we estimated the neutron dose using models based on vault geometry [9].

For the accelerator II, the first reconstruction was done from the ^{60}Co vault to accelerator vault, but a too high photon dose was discovered in point D. Then additional 12 cm of steel was inbuilt. This gave an additional boost to the neutron fluence at the point D, so finally 30 cm of concrete was added, together with the additional vault door shielding, making the neutron equivalent dose per Gy of photon at isocenter much lower.

To analyze the collimator opening dependence, the measurements were performed at all four measuring points for field sizes 0 cm × 0 cm, 10 cm × 10 cm, 20 cm × 20 cm, and 40 cm × 40 cm, respectively, and for gantry angles 0° ("vertical" beam) and 90° ("lateral" beam), respectively.

RESULTS

The neutron dose equivalents produced per 1 Gy of the photon dose at isocenter are presented for four accelerators, measuring positions and beam orientations (tab. 1). The measurements are presented only for the 40 cm × 40 cm collimator opening. The vault of the accelerator II was reconstructed twice, but the presented measurements in tab. 1 are after the final reconstruction. Since the active detector Thermo BIOREM FHT 752 was available only in one centre, those measurements were made only for the accelerators I and II.

The values calculated using the models based on the vault geometry [10, 11] are presented in tab. 2 for comparison with measured values in point C for all accelerators.

Since the accelerator II vault was reconstructed twice after installing the accelerator we presented the measurements during all stages of accelerator II room reconstruction in tab. 3. The measurements were done only in points A and D, because points B and C were not of interest at that moment. The collimator opening was always 40 cm × 40 cm and the gantry was aiming toward point D (gantry angle = 90 degrees). The first reconstruction was done from the ^{60}Co vault to accelerator vault, but a too high photon dose was discovered in point D. Then additional 12 cm of steel was inbuilt. This gave an additional boost to the neutron fluence at point D, so finally 30 cm of concrete was added, together with the additional vault door shielding, making the neutron equivalent dose per Gy of photon at isocenter much lower.

The measured neutron dose equivalents per 1 Gy of the photon dose at the isocenter at positions A, B, C, and D *vs*. field size reflect the neutron scattering properties and depend on the photon beam energy, point of measurement and beam orientation. Some of the results are plotted in fig. 3.

Table 1. The neutron dose equivalents produced per 1 Gy of the photon dose at the isocenter are presented for all accelerators, measuring positions and beam orientations. Measurements are presented for the 40 cm × 40 cm collimator opening

		Gantry angle = 0°				Gantry angle = 90°			
		A [μSvGy^{-1}]	B [μSvGy^{-1}]	C [μSvGy^{-1}]	D [μSvGy^{-1}]	A [μSvGy^{-1}]	B [μSvGy^{-1}]	C [μSvGy^{-1}]	D [μSvGy^{-1}]
I-Mevatron 15 MV	Solid state nuclear tracketched detectors	0.036	0.087	1.7	0.036	0.085	0.049	2	0.085
	Active detector thermo BIOREM FHT 752	0.01	0.083	2.6	0.01				
II-Oncor 18 MV	Solid state nuclear tracketched detectors	0.042	0.08	10	0.04	0.1	0.17	20	0.13
	Active detector thermo BIOREM FHT 752	0.052	0.1	14.3	0.052				
III-Oncor Impression 15 MV	Solid state nuclear tracketched detectors	0.021	0.023	1.4	0.02	0.019	0.019	2.1	0.019
IV-Oncor Expression 18 MV	Solid state nuclear tracketched detectors	0.08	0.083	8	0.093	0.069	0.059	10	0.075

Table 2. Comparison of values measured in the point C and model based calculated neutron dose equivalents produced per 1 Gy of the photon dose at the isocenter for all accelerators

	Accelerator I	Accelerator II	Accelerator III	Accelerator IV
Measured [μSvGy^{-1}]	1.7	10	1.4	8
Kersey [μSvGy^{-1}] [10]	0.47	12.7	0.86	5.85
Wu and McGinley [μSvGy^{-1}] [11]	0.26	4.2	0.4	1.8

Table 3. Neutron dose equivalents per photon Gy at the isocenter at positions A and D measured at accelerator II during three stages of reconstruction. The collimator opening was 40 cm 40 cm and the beam aimed toward measuring point D, with gantry 90 degrees

		A, *G* = 90° [μSvGy^{-1}]	D, *G* = 90° [μSvGy^{-1}]
II-Oncor 18 MV	1 m concrete + 19 cm of steel	0.1	0.24
II-Oncor 18 MV	1 m concrete + 19 cm of steel + 12 cm of steel	0.093	0.29
II-Oncor 18 MV	1 m concrete + 19 cm of steel + 12 cm of steel + 30 cm concrete + door shielding	0.042	0.13

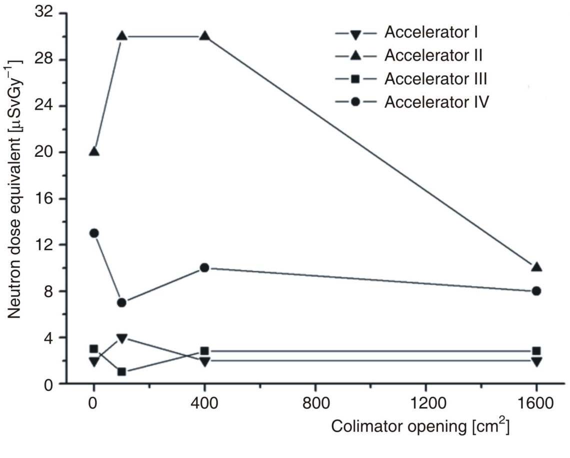

Figure 3. Neutron dose equivalents produced per 1 Gy of the photon dose at the isocenter for all accelerators measured at point C with gantry angle = 0. Collimator openings (photon field sizes at 100 cm from the source) are presented as area in cm^2

DISCUSSION AND CONCLUSIONS

The neutron equivalent doses measured around the four radiotherapy linear accelerators are presented in tab. 1. The measured values are comparable to the published values [12, 13]. As expected, the largest doses were measured in mazes (measuring location C), especially for accelerators with the 18 MV photon beams. When the beam was pointed toward the measuring point D, the measured values in point C for all accelerators rose. This was expected for accelerators I, III, and IV because the neutrons produced leave the head in all directions as the high-*Z* head shielding material has little effect in stopping them. It is not unusual to see a difference in factor of 2 in dose between two gantry angles [9]. Surprisingly, it was also true for accelerator II where the head is at the largest distance from the inner maze entrance when pointing to the point D. It was the expected result in point D due to the production of neutron in metal walls; however, this was also true for all measuring points. We assume that this can be the result of the transparency through the maze wall since the maze wall is only 70 cm thick, made of concrete with unknown density (left from the old ^{60}Co building). Also, it could be that the treatment room wall, strengthened with steel, becomes a photoneutron source that adds to the neutron component in all points when the beam is pointed there. We will do more measurements to confirm this assumption in the near future. Though the accelerator III is also built in the place of ^{60}Co unit, this is not so pronounced due to the lower photon energy (15 MV). This leads to the conclusion that if the accelerator has to be put into the limited space, then a lower energy accelerator should be used.

The inconsistency was found in measured values for accelerator I, point B. Though measured neutron dose equivalent in point C was higher than 90° geometry when the accelerator head was closer to the inner maze entrance, in point B (behind the vault door) it was opposite. This inconsistency will be explored in more details in the near future.

The comparison of measured values, using passive and active detectors comply well (tab. 1), though the main limitation of both measurements was that the calculation was done by using the spectrum which is not calculated especially for every measuring location. The neutron spectrum can vary depending on the wall construction [3, 14] and it certainly introduces a large uncertainty in dose estimation with our detectors which will be analyzed further. Since both detectors use the ^{10}B isotope as converter, they have similar energy dependence that explains similar results in all measured places.

We compared the measured values in point C with values calculated using empirical models based on vault geometry [4], also in point C. The parameters used for model based estimation of neutron dose equivalent in point C explain high dose measurements for the accelerator II since this is the smallest vault with very short maze (d_2 = 3.75 m). Even though the model given by Kersey [10] has conservative nature, the measurements overestimation exists. This will be analyzed further.

The measured neutron dose equivalents variations with field size in measuring point C (a maze door inside the accelerator room) are showed in fig. 3. It can be seen that the neutron dose equivalents are lower for closed than for fully opened jaws, that was already confirmed before [9].

Although, the obtained neutron dose rate in control rooms (point A) of the accelerators was always less than 0.05 μSv/Gy of photon beam at isocenter, meaning 15 μSv/h, this is not negligible from the aspect of personal dosimetry. By using the conservative approach (900 Gy per week, all high beam), we calculated that the neutron dose equivalent per year per person can approach 2 mSv in control room (point A) for the accelerator II after reconstruction. The reconstructions of the accelerator II vault show that if the neutron shielding is not considered it can reach twice this value (tab. 3). Also, the reconstruction using the high-*Z* materials can make neutron flux more pronounced behind and around such barrier, and more attention should be given to the neutron dose equivalent measurements, especially if the occupancy of those areas is high.

This study confirms that shielding from the neutron radiation should be considered when building the vaults for high energy linear accelerators, especially if there are space constraints.

AUTHOR CONTRIBUTIONS

The idea for this paper came as a result of discussions of D. Faj, M. Poje, A. Ivković, and J. Planinić. Preparing and conducting the experiments was done by M. Poje, A. Ivković, H. Brkić, D. Faj, I. Miklavčiš (for Osijek), S. Jurković, Z. Kaliman, and G. Zauhar (for Rijeka). Great help in the preparation of the detectors was by I. Miklavčić. Valuable scientific advice and theoretical foundation was provided by J. Planinić, D. Faj, B. Vuković, and V. Radolić with the valuable contribution of all the authors. The manuscript was written and the figures were prepared by D. Faj. All authors were participating in critical review of the manuscript with valuable suggestions for improvement.

REFERENCES

[1] ***, National Committee on Radiation Protection and Measurements (NCRP), Neutron Contamination from Medical Electron Accelerators, NCRP Report No. 79, NCRP, Washington, DC, 1984

[2] Vuković, B., *et al.*, A Neutron Track Etch Detector for electron Linear Accelerators in Radiotherapy, *Radiology and Oncology, 44* (2010), 1, pp. 62-66

[3] Schraube, H., *et al.*, Neutron Spectra Around Medical Treatment Facilities, *Nucl. Instrum. Methods, 476* (2002), 1-2, pp. 463-467

[4] Becker, J., Brunckhorst, E., Schmidt, R., Investigation of the Neutron Contamination in IMRT Deliveries with a Paired Magnesium and Boron Coated Magnesium Ionization Chamber System, *Radiotherapy and Oncology, 86* (2008), 2, pp. 182-186

[5] Lilley, J. S., In Nuclear Physics, Wiley, Chichester, 2001

[6] Lopez Ponte, M. A., *et al.*, A Catalogue of Dosimeters and Dosimetric Services within Europe – an Update, *Radiation Protection Dosimetry, 112* (2004), 1, pp. 45-68

[7] Aza, E., *et al.*, Instrument Intercomparison in the Pulsed Neutron Fields at the CERN HiRadMat Facility, *Radiation Measurements, 61* (2014), 1, pp. 25-32

[8] Followill, D. S., *et al.*, Neutron Source Strength Measurements for Varian, Siemens, Elekta, and General Electric Linear Accelerators, *J. Appl. Clin. Med. Phys., 4* (2003), 3, pp. 189-194

[9] ***, Radiation Protection in the Design of Radiotherapy Facilities, International Atomic Energy Agency, Safety Report Series 47, Vienna, 2006

[10] Kersey, R.W., Estimation of Neutron and Gamma-Radiation Doses in the Entrance Maze of SL 75-20 Linear Accelerator Treatment Rooms, *Medicamundi, 24* (1979), 1, pp. 151-155

[11] Wu, R. K., McGinley, P. H., Neutron and Capture Gamma Along the Mazes of Linear Accelerator Vaults, *Journal of Applied Clinical Medical Physics, 4* (2003), 2, pp. 162-171

[12] Martinez-Ovalle, S. A., *et al*., Ambient Neutron Dose Equivalent Outside Concrete Vault Room for 15 and 18 MeV Radiotherapy Accelerators, *Radiation Protection Dosimetry, 148* (2012), 4, pp. 457-464

[13] Krmar, M., *et al*., Neutron Dose Equivalent Measured at the Maze Door with Various Openings for the Jaws and MLC, *Medical Physics, 39* (2012), 3, pp. 1278-1281

[14] Falcao, R. C., Facure, A., Silva, A. X., Neutron Dose Calculation at the Maze Entrance of Medical Linear Accelerator Rooms, *Radiation Protection Dosimetry, 123* (2007), 3, pp. 283-287

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НЕУТРОНСКИ ДОЗНИ ЕКВИВАЛЕНТ У ОКОЛИНИ МЕДИЦИНСКОГ ЕЛЕКТРОНСКОГ ЛИНЕАРНОГ АКЦЕЛЕРАТОРА ВИСОКИХ ЕНЕРГИЈА

Мерења неутронског дозног еквивалента извршена су унутар и око четири бункера медицинских линераних акцелератора. Два бункера реконструисана су након замене ^{60}Co, те су просторно била ограничена. Мерења су извршена детекторима нуклеарних трагова LR 115 с конвертором ^{10}B и активним неутронским детектором Thermo BIOREM FHT 742. Детектори су постављени на више места ради процене неутронског доприноса озрачењу особља. Уз то, анализирана је и зависност неутронске дозе о отвору колиматора.

Измерени дозни еквиваленти изван бункера неколико пута су мањи од оних мерених у бункеру. Уз то, измерени дозни еквиваленти око 15 MV линеараног акцелератора значајно су мањи него око 18 MV акцелератора, што посебно вреди за мерења у просторијама реконструисаним након замене ^{60}Co са врло кратким лавиринтом. Међутим, измерени дозни еквиваленти ван бункера свеједно нису занемариви с аспекта личне дозиметрије. Конзервативна рачуница за бункер који је реконструисан након замене ^{60}Co, те има врло кратак лавиринт, показује да би неутронски дозни еквивалент у контролној соби могао достићи 2 mSv по години. Резултати овог истраживања показују да је приликом изградње бункера и просторија за линеарни акцелератор потребно водити рачуна и о неутронском дозном еквиваленту посебно када је простор за изградњу ограничен.

Кључне речи: радиотерапија, електронски линеарни акцелератор,
неутронски дозни еквивалент