Assessment of in vivo dosimetry measurements in electron-based radiotherapy from a statistical perspective*

Aleksandra Kłos-Witkowska[1,*,†] and Vasyl Martsenyuk[1,†]

[1] University of Bielsko-Biala, Willowa St. 2, Bielsko-Biala, 43-300, Poland

Abstract

The following paper presents the results of a statistical analysis of dosimeter and in vivo measurements in electron beam radiotherapy of cancer. The main principles of radiotherapy are described and the differences resulting from the discrepancy between the planned and received doses are summarised. The analysis was performed for electron beams with energies of 9.12 and 15 MeV. The studies showed good agreement between the planned doses and those administered to patients; in a few cases, the discrepancies exceeded 5%. The main source of these discrepancies was an inaccurate treatment planning system and the method of attaching detectors to the patient's skin, which, due to the anatomical shape of the therapeutic area, prevented very precise placement of the detector in the radiation field.

Keywords

radiotherapy, electron beams, statistical analysis, patients, energy

1. Introduction

One of the basic methods of treating cancer patients is radiotherapy [1-3], which is a treatment using ionising radiation that exploits the sensitivity of individual tissues and tumours to radiation. The therapeutic dose of radiation is designed to damage the tumour and inhibit the ability of cells to reproduce without seriously damaging healthy tissue [4-6].

The basic condition for the effectiveness of radiotherapy in cancer treatment is ensuring that the dose administered matches the planned dose. For various reasons, such as malfunctioning of the therapeutic device, insufficient precision of the treatment planning system, human error, and instability of the patient's position during the irradiation session, the discrepancy between the administered dose and the planned dose can reach several percent [7-10]. The standards applicable in radiotherapy, contained in the so-called dosimetry protocols, allow for the possibility of discrepancies, but their maximum value is strictly defined. According to the recommendations of the International Agency for Radiological Units and Measurements, the differences between the planned and delivered doses should not exceed 5%. Some authors even postulate that in order to maintain a high level of treatment, these differences should not exceed 3.5%. Failure to comply with the above recommendations results in a sharp decrease in the probability of cure and the risk of cancer recurrence [11-13]. It is estimated that a 1% change in the absorbed dose relative to the planned dose reduces the probability of cure by approximately 3%. Direct in vivo measurements are an excellent test of the accuracy of dose delivery to the patient, as they also make it possible to determine the causes of errors and correct them[14-16].

The aim of this study is to statistically analyse the results obtained by applying in vivo symmetry in radiotherapy of tumours with electron beams. In vivo dosimetry is performed using EDE semiconductor detectors. The paper presents a histogram of percentage differences between

*BAITmp'2025: The 2nd International Workshop on "Bioinformatics and Applied Information Technologies for medical purpose", November 12-13, 2025, Ben Guerir, Morocco

[1,*] Corresponding author.

[†] These authors contributed equally.

awitkowska@ath.bielsko.pl (A. Kłos-Witkowska); vmartsenyuk@ath.bielsko.pl (V. Martsenyuk)

0000-0003-2319-5974 (A. Kłos-Witkowska); 0000-0001-5622-1038 (V. Martsenyuk)

the planned dose and the dose administered to the patient. The statistical analysis covers 209 cases, and the data comes from one of the hospitals in Silesia, Poland.

1.1. Interaction of electrons with the environment

Electrons are particles with an electric charge. As they pass through an environment, they transfer their energy to it. The manner in which energy is transferred depends on the energy of the electrons and the atomic number of the environment. The energy of electrons is lost as a result of collisions with atoms in the environment (excitation and ionisation) and as a result of deceleration in the environment. In the case of deceleration, part of the electron's energy is converted into bremsstrahlung (electromagnetic radiation), which is observed especially when the environment has a high atomic number. The total loss of electron energy dE over a distance dl in the environment is the sum of the energy losses transferred to ionisation and bremsstrahlung, which can be written as follows:

$$\frac{dE}{dl}=\left(\frac{dE}{dl}\right)_{jon}+\left(\frac{dE}{dl}\right)_{prom}$$

For a given environment, the value of energy loss dE of electrons along the path dl is called the linear damping capacity and is denoted by S(E). The linear damping capacity is a function of electron energy, which can be written as:

$$\frac{dE}{dl}=S(E)$$

If we take into account that an electron loses its energy in an environment with a density of q, we can divide the linear braking capacity by the density of the environment. The result is a quantity called the mass braking capacity, denoted by S(E)/ q. Taking into account the energy dissipation by the electron, we can write:

$$\frac{S(E)}{q}=\left(\frac{S(E)}{q}\right)_{jon}+\left(\frac{S(E)}{q}\right)_{prom}$$

From the point of view of the use of electrons in radiotherapy, the loss of electron energy due to ionisation of the environment is significant. The absorption of energy by the environment is, by definition, the dose. By definition, the dose range of electrons used in radiotherapy is between 4 MeV and 25 MeV. Electron beams used in radiotherapy are currently produced mainly in linear electron accelerators.

1.2. From physical phenomena to biological effects

As the electrons in the beam pass through matter, they interact with the atoms of the medium through various processes: inelastic collisions with atomic electrons leading to excitation or ionisation of the medium atoms, inelastic collisions with the nucleus resulting in bremsstrahlung, elastic collisions with medium atoms, and elastic collisions with the nucleus. In an inelastic collision, the electron loses part of its kinetic energy, which is transferred to the electron of the medium atom, causing excitation or ionisation of the atom, or is converted into bremsstrahlung. In an elastic collision, the energy of the electron is distributed among the particles involved in the collision in such a way that the sum of the kinetic energy of the interacting particles before and after the collision is the same.

In biological tissue or water, as well as in other media with a low atomic number, electrons lose their kinetic energy mainly through the ionisation of atoms. The loss of kinetic energy by the beam electron continues until the electron reaches thermal energy and is captured by the atoms of the

medium. At the same time, the atom knocked out of the atom as a result of ionisation, the so-called secondary electron, can cause further ionisation if its kinetic energy is sufficiently high. The primary process in the chain of changes producing a specific biological effect is the ionisation of atoms in the body's cells. Ionisation can disrupt the functionally important chemical structure of the cell and initiate chemical reactions that disrupt cell function. Of particular importance here is the phenomenon of water radiolysis initiated by ionisation, which results in the formation of radicals with high chemical activity and strong biological effects. Radicals cause further chemical reactions that ultimately contribute to the inhibition of enzymatic activity, disruption of protein synthesis and carbohydrate metabolism, and ultimately cause the destruction of the cell's biological system.

1.3. Input Dose measurement

The input dose is defined as the dose in the radiation beam axis at a depth of dmax, where it reaches its maximum value. The input dose is one of the basic pieces of information in treatment planning. In radiotherapy, the entrance dose is determined on the basis of the efficiency of the therapeutic device, i.e. the dose measured for specific geometric parameters (distance: source-skin(SSD), size of the irradiated field (S)). Factors such as the accuracy of determining the efficiency of the device, the correct operation of the systems used to determine the distance d and the irradiation field, the correct positioning of the patient on the treatment table, the stability of the patient's position during therapy, and the correct selection of the irradiation time are reflected in the value of the entrance dose. Direct measurement of this dose during the irradiation session allows us to determine whether the administered input dose is equal to the planned dose and, in the event of a discrepancy, to identify its causes. If systematic errors are found, we add the possibility of eliminating the error in all subsequently treated patients. On the other hand, the detection of a random error makes it possible to correct the value of the administered dose for a given patient in subsequent irradiation sessions. The measurement of the input dose in vivo is performed by attaching a detector to the patient's skin in the axis of the radiation beam.

In order to determine the input dose based on the detector reading, appropriate calibration and correction factors for semiconductor detectors must first be determined in phantom measurements in relation to the ionisation chamber dose measurement. The patient's entrance dose (Dkom) can be expressed as the product of the readings of the detector placed on the skin in the radiation beam axis (Rwej) and the calibration factor (Fwej).

$$D_{kom} = F_{wej} R_{wej}$$

The calibration factor may depend on the size of the irradiation field S, the distance from the source to the irradiated surface SSD, the angle (α) between the line perpendicular to the detector base and the beam axis, and the temperature (t) of the detector.

$$F_{wej} = F_{wej}(S, SSD, \alpha, t)$$

1.4. Input Dose measurement

The output dose (Dwyj) is defined as the dose value in the radiation beam axis at a distance dmax measured from the beam exit point from the irradiated area. The output dose in a patient can be determined based on the reading of a detector placed on the skin in the beam axis on the side of the exit from the irradiation area (Rwyj). This procedure requires the prior determination of appropriate calibration and correction factors (Fwyj). These coefficients are determined on the basis of phantom measurements.

$$D_{wyj} = F_{wyj} R_{wyj}$$

As with the input dose, this coefficient for a given SSD is a function of several parameters: phantom thickness d, irradiation field size S, angle α between the beam axis and the line perpendicular to the detector base, and temperature t. For a given phantom thickness d

$$F_{wej} = F_{wej}(d, SSD, \alpha, t)$$

2. Material and methods

The *in vivo* dosimetry measurement were out with the use of the EDE-5 semiconductors diodes. The detectors were linked to the DPD-510 electrometer (Scanditronix). The 0.6 cm^3 cylindrical ionization chamber (type NE 2571) and the tissue equivalent phantom composed of slabs with the are of 30cmx30cm were used for the calibration of applied detectors. The measurement were performed for patients with the cancer of the lung, chest and neck region. Total number of measurement 208. Patients were irradiated with the 9,12,15,18,22, MEV electron beams, generated by biomedical accelerator Clinac Varian 2300 C/D. Detectors were positioned on the surface of the body at the centre of irradiated field. Results are shown on the histrograms of percentage differences between the planed dose and received one.

3. Results

A key issue in cancer radiotherapy is the development of a method that allows the input dose during irradiation to be determined with high accuracy (in vivo dosimetry).

This method allows for high accuracy in determining the doses administered to patients. Thanks to in vivo dosimetry, discrepancies between the planned dose and the dose administered to the patient can be verified during subsequent radiotherapy sessions. The graph below shows the results of a study conducted on a group of 14 patients with laryngeal cancer. Some patients were irradiated several times. Graph 1 was created for 50 doses and shows the percentage differences between the input doses and the planned doses.

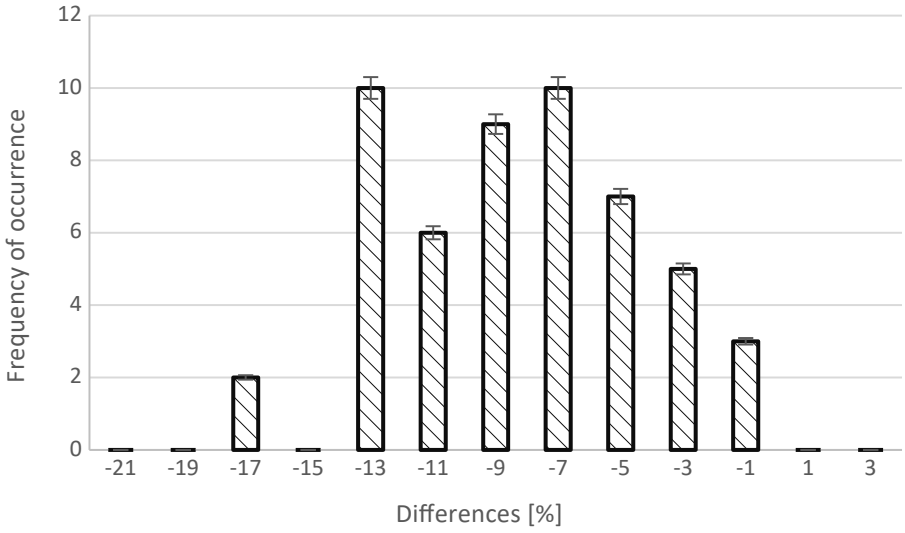

Figure 1: Histogram of differences between planned and measured doses as a percentage of the planned dose for 14 patients (50 doses) (without taking into account radiation absorption in the tray).

Analysis of the presented values (Fig 1) showed that the mean value of the distribution (ŚR) is -9.1% and the standard deviation SD = 4%. Analysis of the causes of the distribution shift revealed a

systematic error resulting from the failure to take into account radiation absorption in the shield support tray. Taking this fact into account leads to the dose distribution shown in Figure 2.

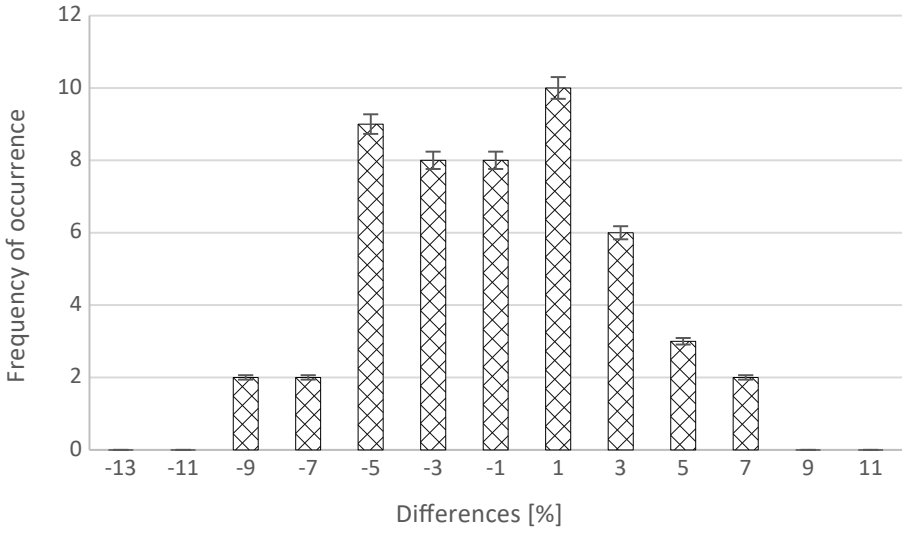

Figure 2: Histogram of differences between planned and measured doses as a percentage of the planned dose for 14 patients (50 doses) (after taking into account radiation absorption in the tray).

It can be seen that the average value is ŚR=- 2.1%, SD=4%. The use of TLD detectors in in vivo dosimetry has the disadvantage that the measurement results are obtained after some time. It is not possible to correct any errors that may occur during the irradiation session. This disadvantage is eliminated by semiconductor detectors. The method of direct dose measurement during the irradiation session was implemented for EDE-5 semiconductor detectors using electron beams with energies of 9, 12 15, 18, 22 MeV. Radiotherapy was administered to a group of 209 patients with cancer in the neck, chest and lungs. The discrepancies between the dose administered to the patient and the planned dose are presented in the form of a histogram 3

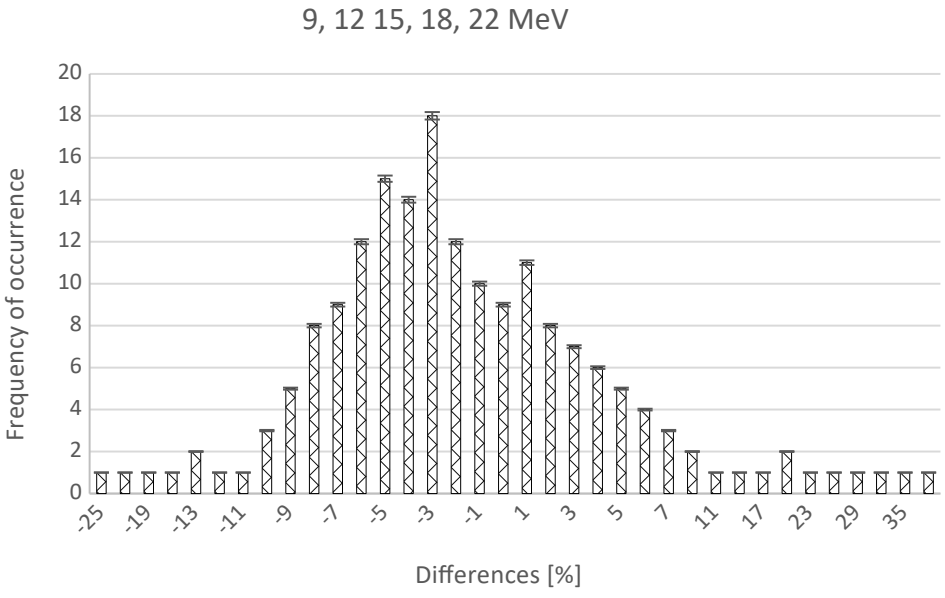

Figure 3: Histogram of differences between planned and measured doses as a percentage of the planned dose for 209 patients with irradiated electron beams with energies of 9, 12 15, 18, 22 MeV.

An analysis of the above chart (Fig 3) shows that the average value of the distribution obtained is 2.48%, with the extreme values of the percentage differences being -25% and 37%.

Next, an analysis was performed for individual electron beam energies, and thus histogram 4 shows the percentage differences between the measured and planned doses for the 9 MeV electron beam.

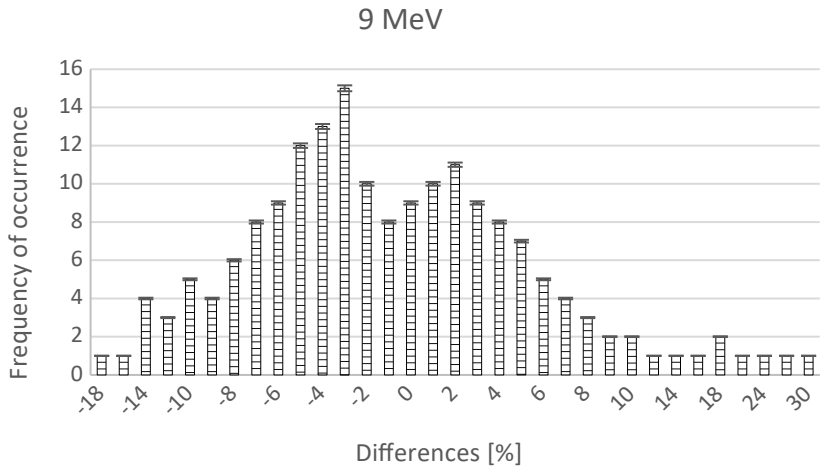

Figure 4: Histogram of differences between planned and measured doses as a percentage of the planned dose for 177 patients with irradiated electron beams with energies of 9 MeV.

Histogram 4 was created for 177 patients irradiated with a 9 MeV electron beam. The mean value of the obtained distribution is 3.02%, with extreme percentage differences of -18% and 30% and a standard deviation not exceeding 2%

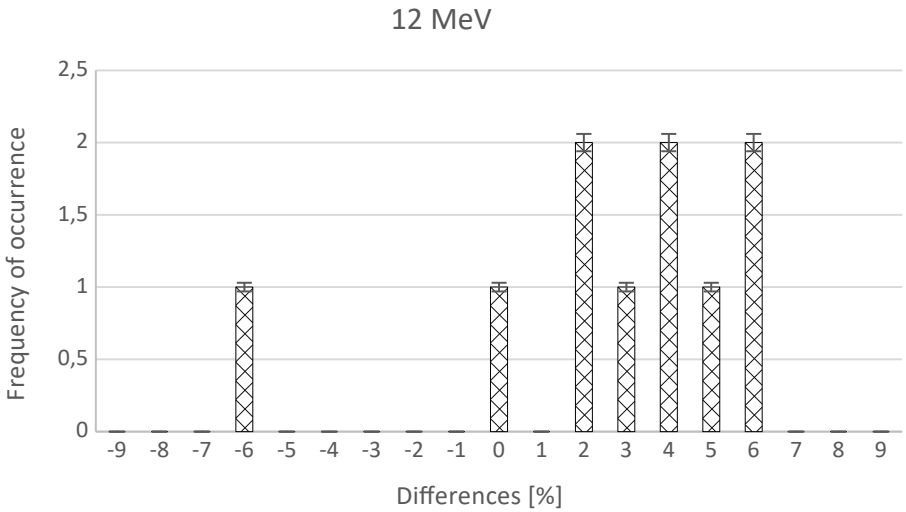

Figure 5: Histogram of differences between planned and measured doses as a percentage of the planned dose for 10 patients with irradiated electron beams with energies of 12MeV.

On Figure 5 the results of irradiation with a 12 MeV electron beam for 10 patients is presented. The mean value of the obtained distribution is 0,5%, with extreme percentage differences of -6% and 6% and a standard deviation not exceeding 1%

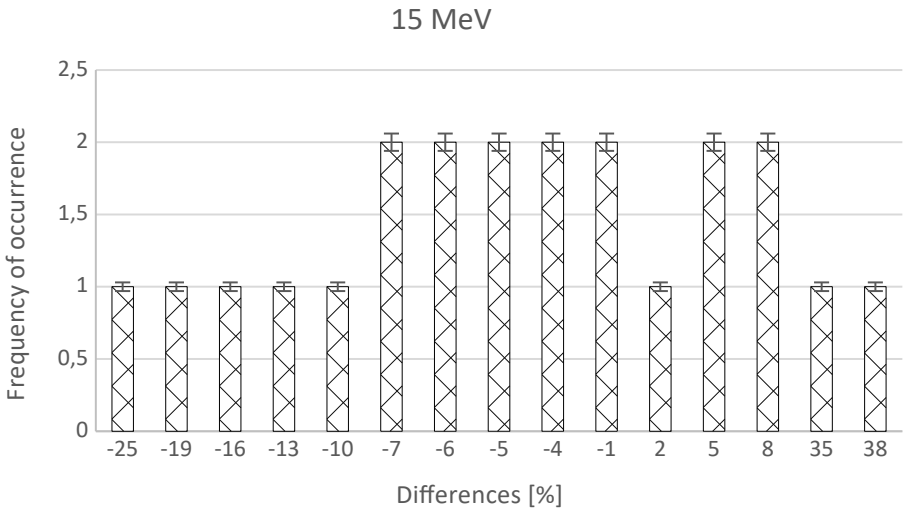

Figure 6: Histogram of differences between planned and measured doses as a percentage of the planned dose for 22 patients with irradiated electron beams with energies of 15MeV.

Histogram 6 was created for 22 patients irradiated with a 15 MeV electron beam. The average value of the distribution obtained is 1.47%, while the standard deviation is 0.51. Extreme percentage differences are -25% and 38%.

Hospital practice shows that radiotherapy with electron beams of 18 and 22 MeV energy is performed extremely rarely, hence the number of cases collected for the following analysis is too small and is not taken into account in the final summary.

4. Summary and final conclusions

Verification measurements of doses in patients based on in vivo symmetries indicate a high degree of consistency between planned doses and doses administered to patients. Only in a few cases do the discrepancies between the planned and administered doses significantly exceed 5%. In these cases, a thorough analysis of the patient's irradiation process was performed. It was found that the main source of the discrepancies was the treatment planning system, which automatically calculates the dose for electron beams. The influence of other factors on the above-mentioned differences was also analysed, such as the influence of the anatomical shape of the irradiated area, the accuracy of SSD setting, and the like. It turned out that a significant factor contributing to the overestimation of the intended dose was the fact that the directors were fixed in a few cases away from the surface of the patient's body, which in turn meant that the detector was located at a slightly shorter distance from the beam source than on the surface. It is extremely difficult to accurately determine the extent of dose overestimation resulting from the director's fixation, because while it is possible to accurately calculate the SSD correction value, it is difficult to determine the effect of backward scatter reduction on the detector reading due to the absence of a small layer of air between the detector fixation and the patient's skin. No significant human factor influence was found (technicians' errors that may occur when positioning the patient on the treatment table and setting the correct irradiation parameters, i.e. SSD distance, irradiation time, etc.).

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] Vaidya, J.S. Principles of cancer treatment by radiotherapy. Surgery (Oxford) 42.3 (2024): 139–149. https://doi.org/10.1016/j.mpsur.2023.12.001.

[2] Webster, M., Podgorsak, A., Li, F., Zhou, Y., Jung, H., Yoon, J., Dona Lemus, O., Zheng, D. New Approaches in Radiotherapy. Cancers 17.12 (2025): 1980. https://doi.org/10.3390/cancers17121980.

[3] Rooney, M.K., Rosenberg, D.M., Braunstein, S., Cunha, A., Damato, A.L., Ehler, E., Pawlicki, T., Robar, J., Tatebe, K., Golden, D.W. Three-dimensional printing in radiation oncology: A systematic review of the literature. J. Appl. Clin. Med. Phys. 21 (2020): 15–26.

[4] Calvo, F.A., Krengli, M., Asencio, J.M., Serrano, J., Poortmans, P., Roeder, F., Krempien, R., Hensley, F.W. ESTRO IORT Task Force/ACROP recommendations for intraoperative radiation therapy in unresected pancreatic cancer. Radiother. Oncol. 148 (2020): 57–64.

[5] Akdeniz, N., Kaplan, M.A., Urakci, Z., Kucukoner, M., Karhan, O., Isikdogan, A. P2.01-49 Comparison of Radiotherapy Concurrent Weekly Treatment in Locally Advanced Unresectable Non Small Cell Lung Cancer. Journal of Thoracic Oncology 13.10 (Suppl.) (2018): S683–S684. https://doi.org/10.1016/j.jtho.2018.08.1103.

[6] Krishnan, P., Narayan, M., Divya, B., Kumar, T.D., Kumar, A.R., Krishnan, R. Oral manifestations of multiple myeloma – A systematic review. Oral Oncology Reports 10 (2024): 100485. https://doi.org/10.1016/j.oor.2024.100485.

[7] Saravanan, K., Narayan, M., Rajkumar, K. The deregulated physiology in oral squamous cell carcinoma – a brief review. Oral Oncology Reports 10 (2024): 100324.

[8] Łobodziec, W., Orlef, A., Maiakowski, Z. Metoda bezpośredniego pomiaru dawki promieniowania X lub gamma u chorych napromieniania innych wiązkami zewnętrznymi. Nowotwory 46 (1996): 67–78.

[9] Moscovici, S., Kaye, A.H., Candanedo, C., Cohen, J.E., Shoshan, Y., Spektor, S. Impact of extent of resection and adjuvant radiation therapy in the progression free survival in patients with spheno-orbital meningioma. Journal of Clinical Neuroscience 129 (2024): 110837. https://doi.org/10.1016/j.jocn.2024.110837.

[10] Łobodziec, W., Orlef, A., Maiakowski, Z. Dozymetria in vivo detektorami TLD dla oceny precyzji radioterapii nowotworów w obrębie głowy i szyi. Nowotwory 43 (1993): 101–107.

[11] Motta, S., Yukihara, E.G. Assessing dose rate effects in TL and OSL dosimeters: A critical look into dose rate models. Radiation Measurements 179 (2024): 107305. https://doi.org/10.1016/j.radmeas.2024.107305.

[12] Kuswanto, H., Mubarok, R. Classification of Cancer Drug Compounds for Radiation Protection Optimization Using CART. Procedia Computer Science 161 (2019): 458–465. https://doi.org/10.1016/j.procs.2019.11.145.

[13] Nurhas, I., Aditya, B.R., Geisler, S., Pawlowski, J. Why Does Cultural Diversity Foster Technology-enabled Intergenerational Collaboration? Procedia Computer Science 161 (2019): 15–22. https://doi.org/10.1016/j.procs.2019.11.094.

[14] Konar, S.K., Maiti, T.K., Bir, S.C., Kalakoti, P., Bollam, P., Nanda, A. Predictive Factors Determining the Overall Outcome of Primary Spinal Glioblastoma Multiforme: An Integrative Survival Analysis. World Neurosurgery 86 (2016): 341–348.e3. https://doi.org/10.1016/j.wneu.2015.08.078.

[15] Tung, C.J., Wang, L.C., Wang, H.C., Lee, C.C., Chao, T.C. In vivo dose verification for photon treatments of head and neck carcinomas using MOSFET dosimeters. Radiation Measurements 43.2–6 (2008): 870–874. https://doi.org/10.1016/j.radmeas.2007.11.050.

[16] Berger, T., Reitz, G., Hajek, M., Vana, N. Comparison of various techniques for the exact determination of absorbed dose in heavy ion fields using passive detectors. Advances in Space Research 37.9 (2006): 1716–1721. https://doi.org/10.1016/j.asr.2005.12.010.