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MATRIX METAL COLLIMATORS STUDIES FOR THE SPATIALLY FRACTIONATED RADIATION THERAPY. TUNGSTEN, TANTALUM AND IRON COLLIMATORS

Radiation therapy has long been a cornerstone in cancer treatment, but its effectiveness is often limited by the need to spare healthy tissues while targeting tumors. Spatially fractionated radiation therapy, a novel approach, addresses this challenge by dividing the primary radiation beam into multiple minibeams, thereby increasing the peak-to-valley dose ratio (PVDR) and potentially enhancing therapeutic outcomes. In this study, we explore the optimization of minibeam generation using mechanical collimators composed of Tungsten, Tantalum, and Iron, three high-density materials well-suited for radiation therapy applications. The primary objective of this research is to improve the efficiency of spatial dose fractionation, a critical factor in reducing radiation-induced damage to normal tissues. The PVDR is a key parameter in fractionation, with a PVDR of 8 or higher considered optimal. Minimizing the valley dose is equally crucial to preserve healthy tissue architecture and support tissue repair. To achieve efficient spatial fractionation, we present a new type of metal matrix collimator with modular design features, including 2.5 mm thick plates made of Tungsten, Tantalum, or Iron. These materials are chosen for their hardness, facilitating mechanical processing, and reducing the need for post-processing. Central plates incorporate 1 mm wide slits, creating channels for beam fractionation. A 5x5 hole matrix with 1 mm diameter and 2.5 mm pitch covers an area of 11x11 mm², providing flexibility in collimator size and geometry. Specialized collimator modules ensure alignment when stacked.

This work introduces a novel metal matrix collimator design and presents promising results for improving spatial dose fractionation in radiation therapy. Monte Carlo simulations provide insights into optimizing collimator features for maximum efficiency. These findings support further biological studies to evaluate the impact of fractionation on both normal and tumor tissues, paving the way for the practical implementation of collimation in clinical practice. Spatially fractionated radiation therapy holds great promise as an alternative approach for treating complex cases in cancer therapy, potentially enhancing patient outcomes and reducing radiation-induced side effects.

***Keywords**: radiation therapy, spatial fractionation, collimators, Geant4 simulations, dose fractionization, X-ray beams.*

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ДОСЛІДЖЕННЯ МАТРИЧНИХ МЕТАЛЕВИХ КОЛІМАТОРІВ ДЛЯ ПРОСТОРОВО-ФРАКЦІОНОВАНОЇ ПРОМЕНЕВОЇ ТЕРАПІЇ. ВОЛЬФРАМОВІ, ТАНТАЛОВІ ТА ЗАЛІЗНІ КОЛІМАТОРИ

Променева терапія вже давно є одним із основних інструментів у лікуванні раку, але її ефективність часто обмежується дозовим навантаженням на здорові тканини які лежать на шляху до пухлини. Просторово фракціонована променева терапія, новий підхід, вирішує цю проблему, розділяючи первинний пучок випромінювання на кілька міні-променів, таким чином знижуючи дозу опромінення здорових тканин і потенційно покращуючи терапевтичні результати.Мета даного дослідження це оптимізація генерації міні-пучків за допомогою металевих матричних коліматорів, що будуть виготовлені з вольфраму, танталу та заліза, трьох матеріалів високої щільності, які добре підходять для застосування в променевій терапії. Основна мета цього дослідження полягає в тому, щоб підвищити ефективність просторового фракціонування дози, що є критичним фактором у зменшенні спричиненого радіацією пошкодження нормальних тканин. PVDR є ключовим параметром у фракціонуванні, при цьому PVDR 8 або вище вважається оптимальним. Для досягнення ефективного просторового фракціонування ми представляємо новий тип металевого матричного коліматора з модульними конструктивними особливостями, включаючи пластини товщиною 2,5 мм із вольфраму, танталу або заліза. Ці матеріали вибрано через їхню відносну простоту механічної обробки. Центральні пластини містять щілини шириною 1 мм, які створюють канали для фракціонування пучка. Матриця отворів 5x5 з діаметром 1 мм і кроком 2,5 мм займає площу 11x11 мм². Спеціально розроблена геометрія коліматора забезпечує вирівнювання при складанні. Ця робота представляє нову конструкцію коліматора з металевою матрицею та представляє багатообіцяючі результати для покращення просторового фракціонування дози в променевій терапії. Моделювання методом Монте-Карло дає змогу покращити геометрію коліматора для досягнення максимальної ефективності фракціонування. Результати цієї роботи будуть використані для подальших досліджень для оцінки впливу фракціонування як на нормальні, так і на пухлинні тканини, відкриваючи шлях для практичного впровадження колімації в клінічній практиці. Просторово фракціонована променева терапія має великі перспективи як альтернативний підхід до лікування складних випадків раку, потенційно покращуючи результати лікування пацієнтів і зменшуючи побічні ефекти, спричинені радіацією.

***Ключові слова:** променева терапія, просторове фракціонування, коліматори, моделювання Geant4, фракціонування дози, рентгенівські пучки.*

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Introduction. Dose tolerance of normal tissues is the main problem the radiation therapy. To decrease radiation impact on the healthy cells there was offer to use a new conception, based on splitting main beam on many minibeams. This is a new technique that is mainly being researched in tandem with proton therapy. But proton therapy is much less common than classical radiation therapy, which uses gamma quanta and electrons with energies up to 25 MeV. The previous studies [1] showed effective fractionation and potential for the next research. Main aim of this work is optimization of generated minibeams by mechanical collimators. The main parameter of fractionization is peak-to-valley-dose-ratio (PVDR). The minimum dose in the central region between two beams is named valley dose and the dose in the center of the beam is the peak dose. The ratio between peak and valley doses is called peak-to-valley dose ratio and plays a pivotal role in biological response. High-quality fractionation is considered with the parameter PVDR 8 and higher. In addition, it is essential that the valley dose is kept to a minimum to ensure the preservation of normal tissue architecture and survival of sufficient cells needed for healthy tissue repair. It was hypothesized that the microscopic lesions in the micro/mini-beams paths are repaired by the minimally irradiated cells contiguous to the irradiated tissue slices [2]. This reparation effect was observed in experiments with high energy (MV) photons. Spatially fractionating is very important techniques for the x-ray or electron radiation therapy that are more spread in most part of countries and cheaper than hardon therapy.

Methods. The present paper demonstrates the next research stage of the metal matrix collimators for minibeam radiation therapy. We discover efficiency collimators made out of Tungsten, Tantalum and Iron. Also there have been made modification of collimator geometry. Collimators are made out of 2,5 mm thickness plates. This decision has several advantages. Tungsten and Tantalum are very hard metals for mechanical processing, in this case, thick plates are the best choice. Collimators are designed so, that the plates require minimal post processing. Such modular system provides to variate collimator size and geometry. It allows to tune it for different beam energies and types. Central plates have special 1mm width slits. These slits create channels for the beam fractionization when collimator block is assembled. The collimator design presented on the Fig.1 will be made of tungsten or tantalum plates. Beam splitting provides by hole matrix 5×5, 1 mm diameter and 2.5 mm pitch, area covering 11×11mm^2. Collimator modules have specific form for the mounting one on top of the other to avoid displacement (see Fig.2).

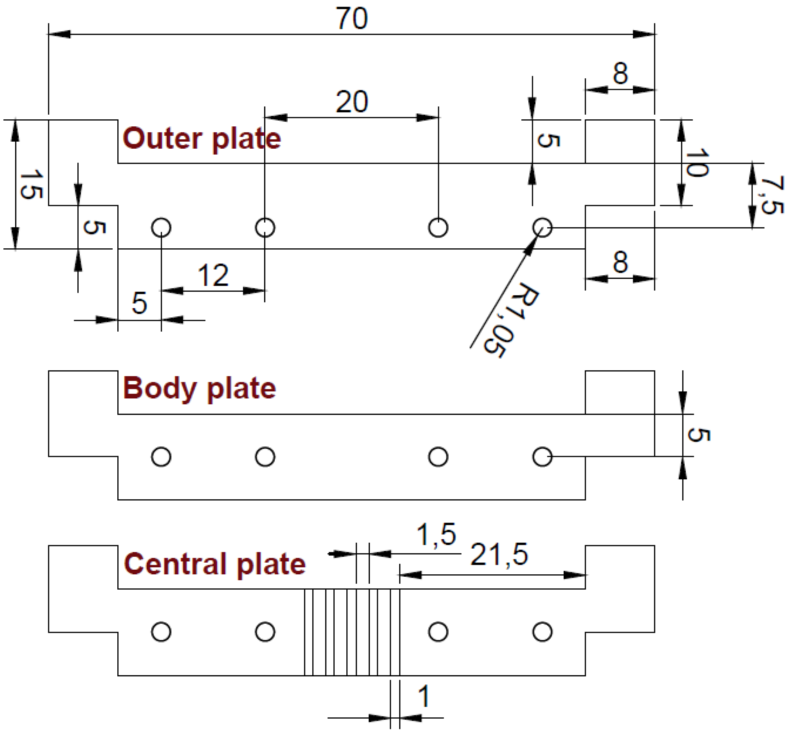

Fig. 1. **Drafts of the collimator plates. Outer plates have shifted mounting holes. It provides precise assembling of the blocks**

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For experimental studies of collimator efficiency there will be used TimePix detector. This is pixel semiconductor with 16x16mm and 256x256 pixels sensor area. The detector allows to get 2-dimension picture of the beam profile in real time [3].

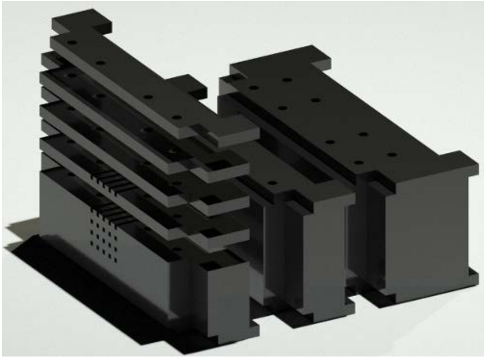

Fig. 2. **3D model of the tungsten collimator.**

Results. The Monte Carlo simulation application Geant4 version 10.6 and Fluka version 4-1.1 ware used for the modeling. For Geant4 the physics list and parameters recommended by the Geant4 collaboration for radiation therapy applications were used. In particular, QGSP_BERT_HP physics list and range cut of 100 µm was considered for all the particles.

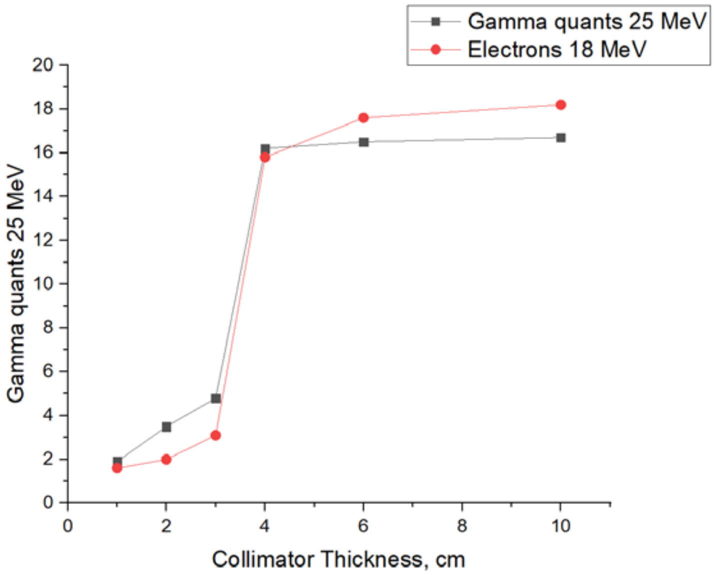

Fig. 3. **PVDR for different thickness tungsten collimator for gamma quants 25MeV and electrons 18MeV**

Results of simulation show possibility for high-rate ionization radiation fractionization. Several types and geometries of collimators were investigated to assess the possible gain in tissue sparing with respect to seamless irradiation. Detailed results of simulation for new one will be presented in the full paper.

Discussions. The modular design of our collimators, with its adaptable size and geometry, provides an essential advantage. It allows for tailoring the collimation to specific beam energies and types, thus accommodating diverse clinical scenarios. The incorporation of central slits effectively generates minibeams, optimizing the peak-to-valley dose ratio (PVDR) and ensuring minimal valley dose, both of which are critical for achieving therapeutic success.

While our study primarily focuses on the technical aspects of collimator design and simulation, the ultimate goal of spatially fractionated radiation therapy is to benefit patients. Future biological studies are warranted to assess the clinical impact of fractionation on both normal and tumoral tissues. Understanding how this approach affects tissue repair mechanisms and overall treatment outcomes is crucial for its practical implementation.

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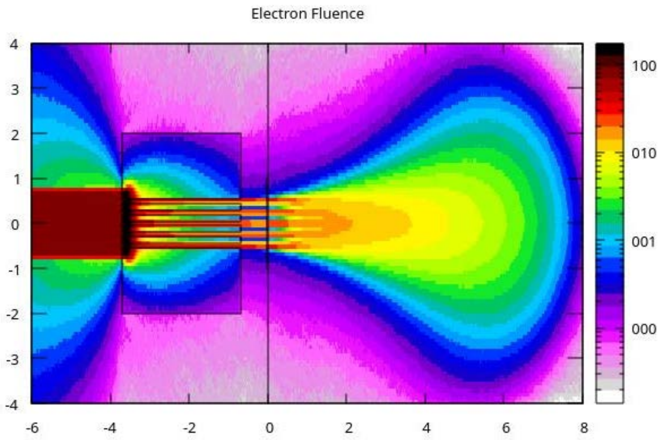

Fig. 3. **Beam distribution in the tungsten collimator (3 cm width) for electron beam 18MeV. After passing the collimator, the minibeams penetrate into PMMA at x=0.**

The successful implementation of spatially fractionated radiation therapy with metal matrix collimators requires careful consideration of clinical workflows and patient-specific treatment planning. Future research should focus on translating these findings into clinical practice, addressing practical challenges, and ensuring safe and effective treatment delivery.

Conclusions

In the present work, a new type of matrix collimator made out of Tungsten, Tantalum and Iron for the shaping mini beams has been simulated and tested to improve the efficiency of the spatial dose fractionation for different types of ionizing radiation.

The Monte Carlo simulation code has been developed to optimize the features (material, thickness, etc.) of collimating systems (multi slits or matrix) to produce optimal multi-beam structures for maximum efficiency of spatially fractionated radiation therapy It has been shown that the high levels of delivery dose fractionization can be achieved for x-rays and electrons.

The general conclusion is that fractionation seems to offer a promising alternative to treat delicate cases.

Following this results, biological studies are warranted to assess the effects of fractionation on both normal and tumoral tissues, for which the practical implementation of collimation seems justified.

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