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A Multileaf Collimator for Proton Radiotherapy

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Studies at the Medical Technical Complex (MTC) of the Joint Institute for Nuclear Research (Dubna) developed an automatic multileaf collimator (MLC) under the working name Aura for forming therapeutic proton beam of defined cross-sectional shape (aperture) for use in a passive 3D conformal radiotherapy in the treatment of oncological disease of the head and neck. A prototype collimator was constructed using four pairs of leaves and was subjected to a series of experimental tests whose results satisfied the requirements. A full-scale MLC will be used as one of the main devices in the new dynamic irradiation system for deep-seated targets of complex shape.

Introduction

External proton beam therapy is widely used in the treatment of various malignant and benign neoplasms [1]. The main task in this treatment is that of delivering the maximum absorbed dose of ionizing radiation to tumors with minimal irradiation of adjacent healthy tissues. In other words, the dose distribution generated must be maximally conformal.

At the Medical Technical Complex (MTC) of the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research, the Phasotron accelerator is used to implement a high-precision passive method for 3D conformal proton radiotherapy [2]. One of the main elements of this method is a custom-made collimator designed to form a therapeutic proton beam of defined cross-sectional shape (aperture) from a wide initial beam by complete deceleration of the unused part in the collimator body and, at the same time, allowing passage of the remaining part of the beam without alteration. The shape of the collimator aperture corresponds to the shape of the patient's tumor in the selected direction of irradiation.

The MTC currently uses individually shaped collimators cast from Cerrobend. This type of collimators has a high degree of conformity, though there is a series of drawbacks: each collimator is individual and can be used only for a specific patient and direction of irradiation; there is no opportunity for automatic substitution of the collimator when the angle of irradiation changes; there is an increase in the dose received by personnel during the collimator replacement process; the collimator is complex to prepare, and casting into molds is hazardous. These drawbacks were taken into account in developing a multileaf collimator (MLC) under the working name Aura providing automatic alteration of the aperture by using a large number of thin moveable metal plates (leaves).

Use of the Aura MLC significantly decreases radiation loading on the patient's healthy tissues and reduces the duration of irradiation sessions by using new irradiation methods such as dynamic irradiation and irradiation with intensity-modulated beams. The need for special locations for preparing shaped collimators and storing used collimators carrying radioactivity after irradiation disappears. Dose loads on personnel are reduced.

The Aura MLC will be the main element in a dynamic irradiation system for deep-seated targets of complex shape under development at the MTC [3]. The dynamic patient irradiation system is a programmable system which will include an MLC, an automatic range shifter [4] for precise control of proton beam energy, and special software. The dynamic irradiation method allows proton therapy of tumors to be delivered with an unmodified (narrow) Bragg peak, layer-by-layer in depth, with a greater conformity than obtained with the passive 3D conformal proton radiotherapy based on individually shaped collimators currently used at the MTC.

The Aura MLC can also be used for intensity-modulated proton therapy (IMPT) [5], in which the beam aperture for every irradiation direction changes automatically during treatment, such that different parts of a

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tumor can be irradiated at greater or lesser intensity from one direction, which is impossible using collimators with fixed apertures.

Design and Technical Characteristics of the Device

Studies at the MTC have developed a design for a full-scale Aura MLC with a maximum aperture of 100 × 100 mm [6]. A prototype collimator with four pairs of leaves has been constructed, with aperture 100 × 15 mm for a series of electromechanical and dosimetric experiments.

The full-scale Aura MLC (Fig. 1) includes two symmetrical blocks, each of which contained 34 steel leaves of identical thickness, 2.9 mm, located within a steel casing symmetrical with respect to the median plane of the collimator. Each leaf has an individual drive (actuator), which can operate via a retractable drive screw attached at one end to the end of the leaf to move it independently of the other leaves in the block, perpendicular to the median plane of the collimator through which the axis of the proton beam passes. Movement is from one edge of the maximum possible aperture of the MLC to the other edge and amounts to 100 mm. The leaves are Π-shaped in profile in the direction of the beam and are collected into blocks such that the protruding upper part of the profile of the leaf is within the recess in the lower part of the profile of the neighboring leaf (Fig. 2). This shape of the leaves and their assembly into a block allows the parasitic interleaf transmission on passage of the unused part of the beam through the leaf to be decreased. Thus, considering the most likely trajectories of particles in the incident beam (dotted lines *a*, *b*, *c*, *d* in Fig. 2), the minimum possible thickness of the leaves material along the particle trajectories *a*, *b*, and *c* is at least 5.6 cm of steel. This thickness can completely decelerate the beam with the maximum proton energy of 220 MeV used for radiotherapy. The total width of each leaf in the beam is 12 cm.

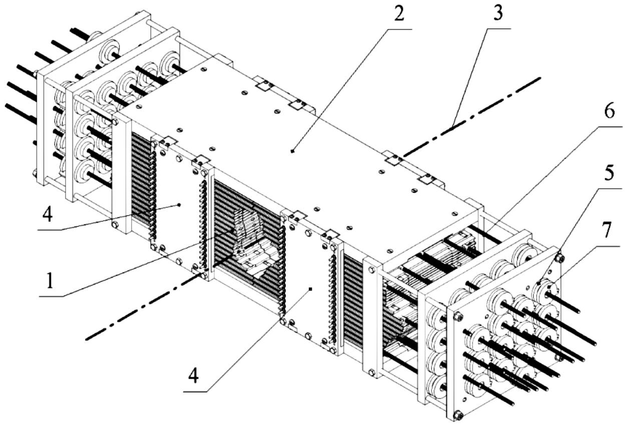

Fig. 1. Construction of the Aura multileaf collimator: 1) set of leaves in block; 2) casing; 3) geometrical axis of collimator; 4) side plates; 5) drives (actuators); 6) mobile drive screws; 7) encoders.

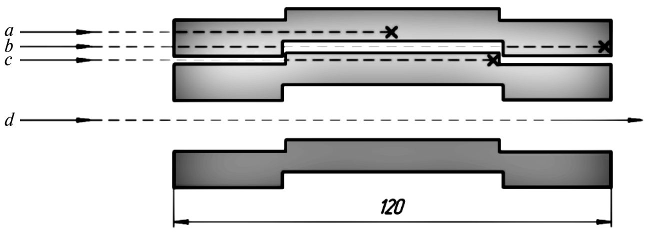

Fig. 2. Positioning of leaves in a block and possible beam particle trajectories (*a*, *b*, *c*, *d*). At complete closure of the MLC aperture, 93% of incident beam *a* passes, compared with only about 7% of beams *b* and *c*.

The ends of the leaves on the side of the median surface of the collimator forming its aperture are made as alternating Π-shaped projections and recesses such that the projections and recesses in the leaves in one block align and alternate in a checkerboard pattern with those in the opposite blocks. To achieve complete overlap at a specified level on closure of the corresponding paired leaves from different blocks, the total thickness of the projections of these leaves in the beam path amounts to about 12 cm of steel, which also decreases parasitic interleaf transmission.

Weight in the blocks is distributed and the leaves are kept in the strictly horizontal position relative to the collimator casing by means of guide grooves on the side surfaces, these containing ball bearings attached in side plates. Each leaf also has guide slots containing separators with balls ensuring the requisite gap between leaves, which is 0.1 mm.

The actuator is able to provide movement of the leaf at a speed of at least 10 mm/s. Each drive is fitted with a position sensor consisting of a multiturn optical encoder measuring leaf movement to an accuracy of ±0.1 mm per encoder count. Each leaf has a corresponding individual limit switch positioned opposite the end of the leaf furthest from the beam. The limit switches are used to calibrate the position sensors of the device.

The dimensions of the full-scale Aura MLC will be 600 × 150 × 125 mm (with the aperture fully closed) and its weight will be about 34 kg.

Principles of Operation of the Device

For use, the MLC is placed in the therapeutic system for external proton beam therapy such that the geometrical axis of the collimator coincides with the beam axis.

Before starting irradiation, the collimator leaves in both blocks are moved in advance using their individual drives to the positions specified for each leaf, which is controlled by the multiturn optical encoders. The part of the proton beam falling on the side surfaces of the leaves is completely decelerated by the leaf material, while the part passing between the ends of the leaves of opposite blocks forming the beam aperture remains unmoderated. The result is formation of a therapeutic proton beam of the required cross-sectional shape.

The specifications for leaf positions required for forming the aperture are determined individually for each patient and each direction of irradiation using an irradiation planning program [2]. The result of the planning program is an aperture file consisting of a matrix of data on the positions of each leaf relative to the median plane of the collimator. This file is loaded into the computer program controlling the MLC.

Control Unit

The main element of the control unit (Fig. 3) is the MLC controller, which functions as a data input–output bus linking the computer and peripherals such as pulse counters of the encoders and drivers of the control actuators.

Let us consider the operation of the MLC in passive 3D conformal proton radiotherapy using the “step-and-shoot” method [2]. In this method, the MLC aperture is formed first, followed by irradiation. On formation of the aperture, the MLC controller uses data from the computer on the positions of each of the leaves, determines the current leaf positions, and sends start and direction commands to the actuator drivers, which then generate the necessary stepper pulses moving the selected leaves to the required positions.

During the operation of the MLC, the encoders generate pulses and the number of pulses is counted by the individual counters. The MLC controller, operating in real time, sequentially interrogates the counters and compares current leaf positions with those specified. When the specified position is reached, a “stop” signal is generated for the actuator driver of the corresponding leaf. When all leaves are in the required positions, the MLC controller sends a signal to the computer that the collimator is ready for the patient to be irradiated. After irradiation, the operating cycle repeats, with formation of the next aperture of the therapeutic beam.

When the MLC is operated using other algorithms, such as those for dynamic irradiation or methods using intensity-modulated beams, the MLC controller can control leaf movement speed and synchronize its opera-

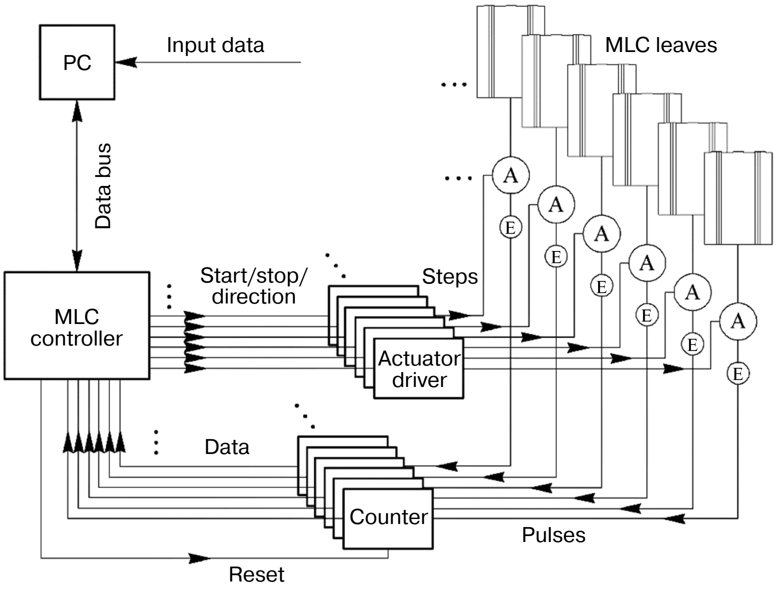

Fig. 3. Functional scheme for Aura MLC control unit: PC — personal computer; E — encoder; A — actuator.

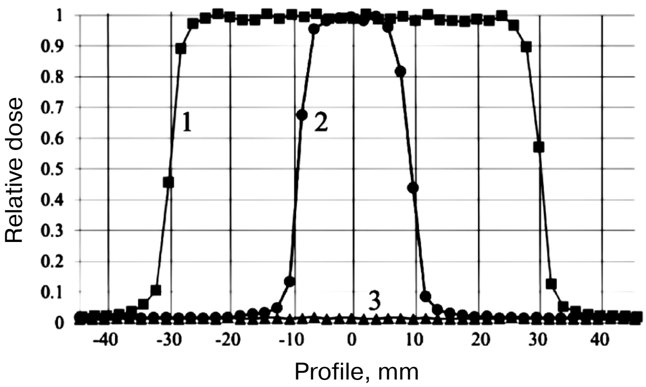

Fig. 4. Collimated proton beam profiles measured with a dose field analyzer: 1) aperture 60 × 15 mm; 2) 20 × 15 mm; 3) closed aperture.

tion with other devices, such as range shifters, dose release systems, etc.

Experimental Testing of Prototype

Testing of the prototype Aura MLC was carried out in the treatment room of the MTC, where the unmodified therapeutic proton beam of uniform cross section, an average energy of 170 MeV, and size 80 × 80 mm was delivered. The MLC was positioned in the beam axis using laser alignment devices. The collimator aperture was changed automatically in accordance with the specified program from the control room. The following aperture parameters were used: 60 × 15 mm and 20 × 15 mm, as well as with the collimator leaves completely closed to check for parasitic interleaf transmission. Measurement of the profiles of collimated beams was performed using a one-dimensional dose field analyzer [7] in the profile measurement mode (Fig. 4). The detector in the analyzer was a miniature p-type silicon diode with a relative sensitivity of about 1 nC/Gy. The detector was moved in water across the axis of the proton beam directly behind the MLC.

The lateral gradient of the collimated beam was measured at an aperture of 60 × 15 mm using GAFChromic EBT3 radiochromic dosimetry film, which was positioned perpendicular to the axis of the beam directly behind the MLC. The film was irradiated at a dose of 1.5 Gy. The resulting value of the lateral gradient at a level of 80-20% was 1.5 mm. No parasitic interleaf transmission was detected.

Electromechanical testing of the device demonstrated that noncumulative leaf positioning errors of up to a maximum of 1 mm could occur with repeated sequential exposure of the apertures (more than 10 times). This was associated with the existence of gaps at the interfaces leaf/screw and nut/screw of the actuator. To avoid this error, the collimator should be recalibrated using the limit switches after every 10 exposures of the aperture.

The measurement results showed good coincidence of the specified and found values of the leaf coordinates, a sufficiently sharp lateral gradient formed by the apertures, and adequate operability of the system as a whole.

Conclusions

The Aura multileaf collimator solves the problem of rapid and accurate formation of a specified cross-sectional shape of the therapeutic proton beam and can be used to implement various irradiation methods with maximum tumor-absorbed dose and minimum irradiation of healthy tissues, i.e., maximizing conformity of treatment.

Furthermore, use of the Aura collimator allows irradiation session duration to be decreased, with reductions in the dose received by personnel due to radioactivity induced in individual collimators and decreases in labor input and cost as compared with the use of shaped collimators.

Additional dosimetric experiments and technical tests of the prototype Aura MLC are planned and will lead to production of a full-size prototype, which will then enter clinical trials with the Phasotron therapeutic proton beam.

REFERENCES

1. Vorob'ev, N. A., et al., "Potentials of proton therapy. Clinical aspects," Russ. Med. Zh., No. 16, 1175-1180 (2017).
2. Agapov, A. V., et al., "A method for three-dimensional proton beam therapy," Pis. EChAYa, **2**, No. 6, 80-86 (2005).
3. Agapov, A. and Mumot, M., "Modeling of dose distribution for proton beam delivering system with the use of multi-particle transport code 'Fluka'," in: AIP Conf. Proc. Nuclear Physics Methods and Accelerators in Biology and Medicine, Vol. 958, New York, USA (2007), pp. 294-297.
4. Agapov, A. V., Mitsyn, G. V., and Shipulin, K. N., "An automated range shifter for proton radiotherapy," Biomed. Eng., **50**, No. 4, 266-269 (2016).
5. Kooy, H. M. and Grassberger, C., "Intensity modulated proton therapy," Br. J. Radiol., **88**, Article ID 20150195 (2015).
6. Agapov, A. V., A Multileaf Collimator for Proton Beam Therapy, RF Patent No. RU 2499621 C2 (2012).
7. Agapov, A. V., Mitsyn, G. V., Shvidkij, S. V., and Shipulin, K. N., "Device for depth-dose distribution measurement of a medical proton beam in radiotherapy," Biomed. Eng., **47**, No. 5, 253-256 (2014).