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# A Dynamic Irradiation Method for Proton Radiotherapy

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*A new technique for dynamic irradiation of deep-seated targets of complex shape has been developed at the Medical-Technical Complex of the Joint Institute of Nuclear Research (Dubna). The technique is implemented using a variable-thickness automated range shifter and a multileaf collimator. The devices were constructed taking cognizance of the characteristics of the existing system for forming radiotherapy proton beams. Preliminary results of dosimetry measurements demonstrated better irradiation field conformity compared to the standard technique of 3D passive conformal proton radiotherapy.*

## Introduction

The main principle in conducting any radiotherapy procedure is that of maximizing the conformity of the radiation. Conformity is the greatest possible correspondence between a homogeneous dose field and the specified volume of the irradiation target. In other words, the method must maximize the dose delivered to the tumor and minimize irradiation of healthy adjacent tissues.

A high-precision passive technique of 3D conformal proton radiotherapy is used at the Medical-Technical Complex (MTC) of the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research [1]. Its implementation is based on the phasotron accelerator facility. The main elements of the device for the implementation of the technique are: a ridge filter — a proton beam modifier, which increases the depth of the Bragg peak depending on the longitudinal size of the target; an individually shaped collimator to form the cross-sectional proton beam profile depending on the projection shape of the target from the irradiation angle; a fixed degrader made from Plexiglass of specified thickness, allowing the optimum proton range for target irradiation at a specified depth to be selected on the basis of beam energy losses in the degrader material; an individual bolus (compensator), which is a degrader of complex shape forming the distal drop-off of the dose distribution immediately beyond the irradiation target.

This method in one form or another is quite widely used in therapeutic practice [2] and provides for irradiation of both superficial and deep-seated targets of complex shape located close to vitally important radiosensitive (critical) structures which must not be irradiated or whose irradiation must be minimized. Data from September 2019 indicate that this method was used at the MTC in more than 1300 patients, mostly with targets located in the head and neck region. Treatment results showed that the method had high efficacy and safety for patients.

However, this method also has a number of drawbacks. We will consider one of these as being the most important. Thus, irradiation of a target of arbitrary shape from a single direction (Fig. 1) produces an area of high dosage to healthy tissues (the so-called tail), which significantly decreases the level of conformity of this irradiation method. In some cases, these “tails” can also fall within the area containing critical structures.

To eliminate this adverse effect of the 3D radiotherapy method, irradiation from several directions (three to eight) can be used, thus significantly decreasing the tail effect on the total dose distribution and increasing the level of irradiation conformity.

However, it should be noted that the opportunity for irradiation of the target from multiple directions may be unavailable, for example, in the case of irradiation of vertebral chondrosarcomas or prostate tumors. Thus, there is a clear need to develop a novel method for proton radio-

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therapy with an improved level of irradiation conformity due to decreased tail effects on the dose distribution with retention of the main principles of therapeutic proton beam shaping using the MTC phasotron.

**Principles of the Dynamic Irradiation Technique**

In dynamic irradiation there is no need to use such elements of the device for 3D passive conformal proton radiotherapy as the ridge filter, the fixed degrader, and the individually shaped collimator. Instead, two beam-forming devices are used: a variable-thickness automated range shifter (ARS) and a multileaf collimator (MLC). The ARS is a device that automatically, following a program, positions a Plexiglass degrader of specified thickness in the proton beam path so as to alter the beam energy (and, as a result, its residual range) within specified limits. The MLC is an automated device that, using a set of thin mobile steel leaves mounted as two opposing blocks, changes its aperture and thus shapes the cross-sectional profile of the proton beam passing through it in accordance with the target size and shape.

We will consider the dynamic irradiation scheme (Fig. 2). On irradiation from one direction, the target is divided virtually into several layers of equal width (1, 2, 3, ..., *n*), whose thickness is selected depending on the width of the Bragg peak of the unmodified proton beam, and is usually 5-10 mm. The distal drop-off of the dose is formed by the individual bolus. Irradiation starts from the distal margin of the target. Transfer from layer to layer towards the proximal margin is by changing (increasing) the thickness of the degrader in the beam using the ARS by an amount equal to layer thickness. The MLC aperture is also altered, depending on target shape for each layer.

The extent of conformity formed by this dose distribution technique is greater than that obtained with the standard passive irradiation method from one direction. The volume of the overirradiated part (the area of the dose distribution formed by the tails) can be decreased by a factor of five or more depending on target shape. Thus, in the irradiation scheme used here, the critical structure and healthy tissues close to the target are exposed to significantly smaller radiation loads.

This technique can also be used in the case of multifield irradiation using a set of individual boluses, which also significantly increases the extent of irradiation conformity. There is no need to use fixed degraders or individual collimators for each of the selected irradiation directions.

**Planning and Execution of the Dynamic Irradiation Method**

Planning of dynamic irradiation uses a special algorithm to compute the dose distribution of the individual beams making up the total dose distribution. The radiologist uses special irradiation planning software to outline the target and close-lying critical structures working from axial slices from a CT scan of the irradiation zone and selects one or several irradiation directions. For each

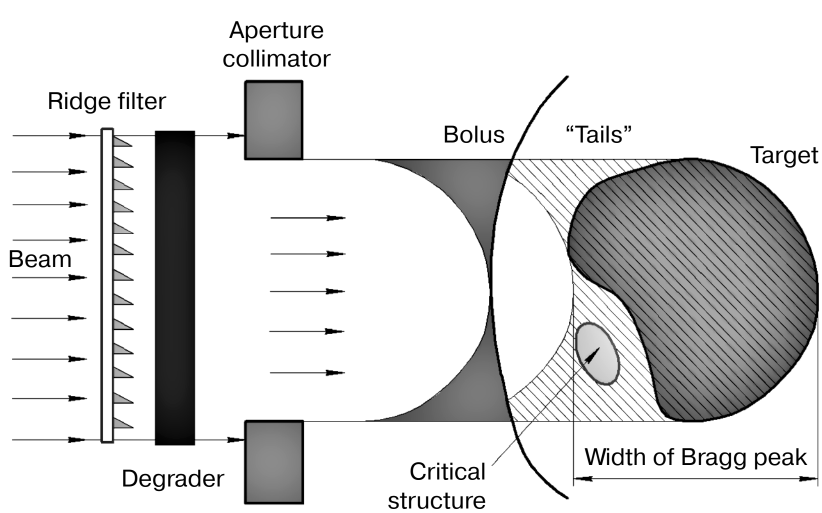


**Fig. 1.** Diagram showing irradiation of target by the method of 3D passive conformal proton radiotherapy with a wide homogeneous beam. The shaded area shows the high-dose region.

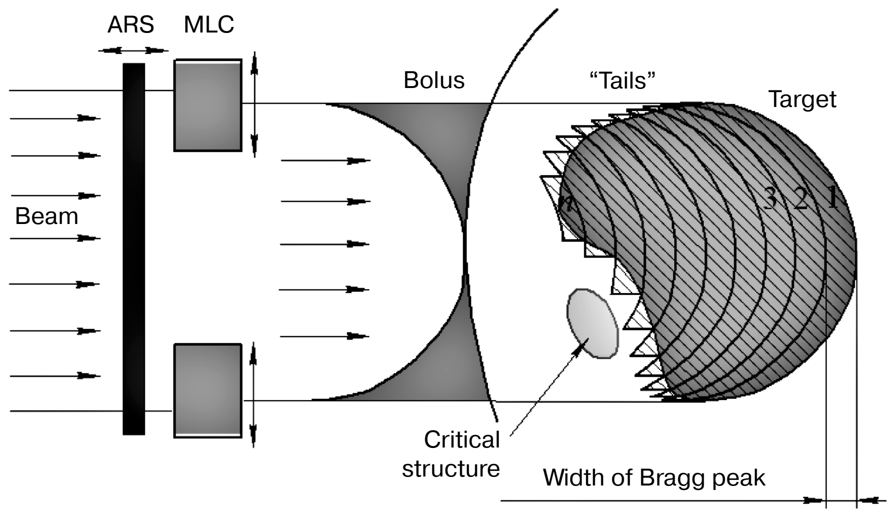


**Fig. 2.** Diagram showing irradiation of target by the dynamic technique. Shaded area shows the high-dose region.

direction, the planning software divides the target into a certain number of layers (*n*) on the basis of the specified proton beam parameters (for example, the width of the unmodified Bragg peak at a level of 90-95% of the maximum dose), computes the weighting (number of monitor units) for each of the *n* beams required for shaping a homogeneous dose distribution throughout the target volume and the magnitude of the mean path for each *n*th beam. The planning software produces files with ARS thicknesses and matrices of data on the positions of each of the MLC leaves shaping the required aperture for each of the *n* layers, along with a file specifying milling parameters for preparation of the individual bolus on a CNC machine. If planning involves selection of multiple irradiation directions, the boluses are computed for each direction.

Before irradiation starts, data files for ARS and MLC are loaded into a computer in the control room, which runs the dynamic irradiation system (Fig. 3). First, the ARS, MLC, and individual bolus are positioned and centered in the beam axis in the radiotherapy procedure room. The patient is immobilized in the treatment chair and the target is positioned in the beam axis using X-ray control images.

After the target position verification procedure, ARS thickness data and MLC leaf position data are transferred from the computer through the dynamic irradiation controller to the control units of the ARS and MLC, respectively. After the operating components of the apparatus are in ready positions, signals are generated to indicate that the system is ready. The computer sends a signal that irradiation should be started to the dose release unit, which in turn sends permission to switch the accelerator on. An ionization chamber (IC)-based monitor, previously calibrated in irradiation dose units at the isocenter point, is located at the output of the beam transporter in the treatment room. On passage of the proton beam, the ionization current from the chamber is received by the signal-processing unit and is converted to a frequency fed to the dose release unit counter.

After counting the required quantity of monitored units for the current layer, the block sends a signal to switch the accelerator off. The computer then sends a signal to the dynamic irradiation controller to move to the next ARS and MLC values for irradiation of the next layer; the operating cycle is repeated. After irradiation of the last layer *n*, the session terminates if only one direction was selected or continues if multiple directions are to be used. To change direction, a staff member enters the procedure room and uses a positioner to rotate the patient around the axis of rotation relative to the beam, thus selecting the next irradiation direction. Staff members also position the new individual bolus. After checking the patient's position, irradiation continues.

## Experimental Verification of the Dynamic Irradiation Technique

The main elements of an apparatus for running the dynamic irradiation technique have been developed and tested at the MTC: a wedge-shaped ARS [3] and an Aura prototype multileaf collimator [4] consisting of four pairs of leaves of thickness 2.9 mm each with a maximum aperture of 100 × 15 mm. These devices provided for experimental testing of the dynamic irradiation technique using proton therapy apparatus at the MTC for determining the operability of the electromechanical devices of the entire installation and identifying drawbacks and errors in planning and delivering irradiation.

The technique was tested experimentally in procedure room No. 1 at the MTC, into which an unmodified therapeutic proton beam with uniform section, mean energy of 170 MeV, and a cross-sectional size of 80 × 80 mm was delivered. The ARS and MLC were mounted on the irradiation stand and centered. A water phantom consisting of a Plexiglass bath of size 200 × 160 × 250 mm filled with distilled water was irradiated. The phantom was placed on the treatment chair and centered with respect to the beam axis. A GAFChromic EBT3 radiochromic dosimetric film of size 100 × 150 mm was placed in the aqueous medium such that the film was aligned along the direction of the beam and the plane of the film was tilted at an angle of 5° to its axis. The projection of the film on the plane perpendicular to the beam axis completely covered the maximum aperture of the MLC.

The irradiation target was a 10-mm-high virtual cylinder with an elliptical base (long axis, 60 mm; short axis, 55 mm). The cylinder orientation in the aqueous medium of the phantom was as follows: the distance from the phantom wall to the cylinder axis along the beam direction was 80 mm, the large axis of the base of the cylinder being perpendicular to the beam axis.

Irradiation was simulated using RayTreat planning software [5] developed specially for proton radiotherapy at the MTC. After outlining the target and selecting the direction of irradiation, the software computed: the bolus, five layers of irradiation by depth, dose distributions for each of the five layers, and the number of monitored units for each beam to form a homogeneous dose distribution to a level of 90%. The total focal dose was 2.5 Gy.

Three radiochromic films were irradiated using different methods. The first film was irradiated by the standard passive method of conformal therapy; the second, by the dynamic technique using a bolus; the third, by the dynamic technique without a bolus. The radiochromic film was first calibrated in a proton beam delivering different doses with a 0.25-Gy step. After irradiation, the film was scanned on a scanner and the dose distribution was digitized. The method of using the radiochromic film has been described in more detail in [6]. The experimental results are presented in Fig. 4.

Comparison of the dose distributions for different irradiation techniques showed that there were no tails of overirradiation on the second and third films. This is indicated by the cross-sectional profile plots of the beam at the proximal margin of the target. The first profile shows tails with dose levels of about 100% at both margins of the plateau. The second and third plots show no tails and the dose plateau level is about 90%. The dose homogeneity

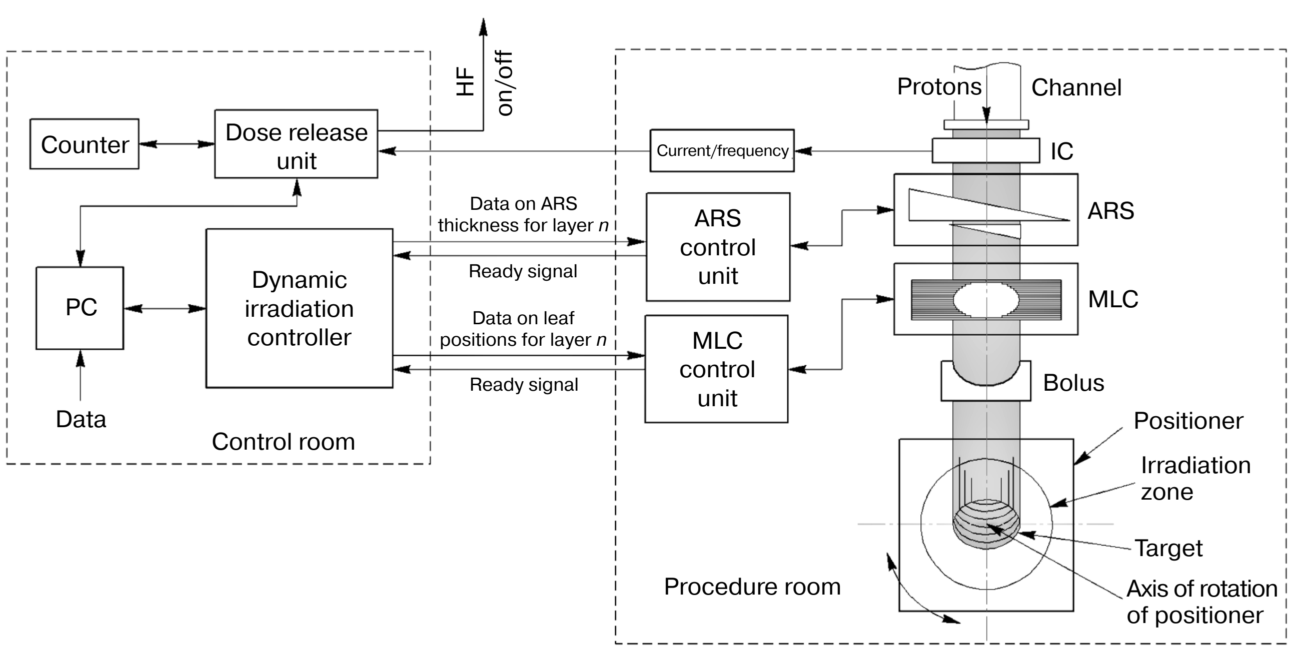


**Fig. 3.** Block diagram of the apparatus system developed here for dynamic irradiation.

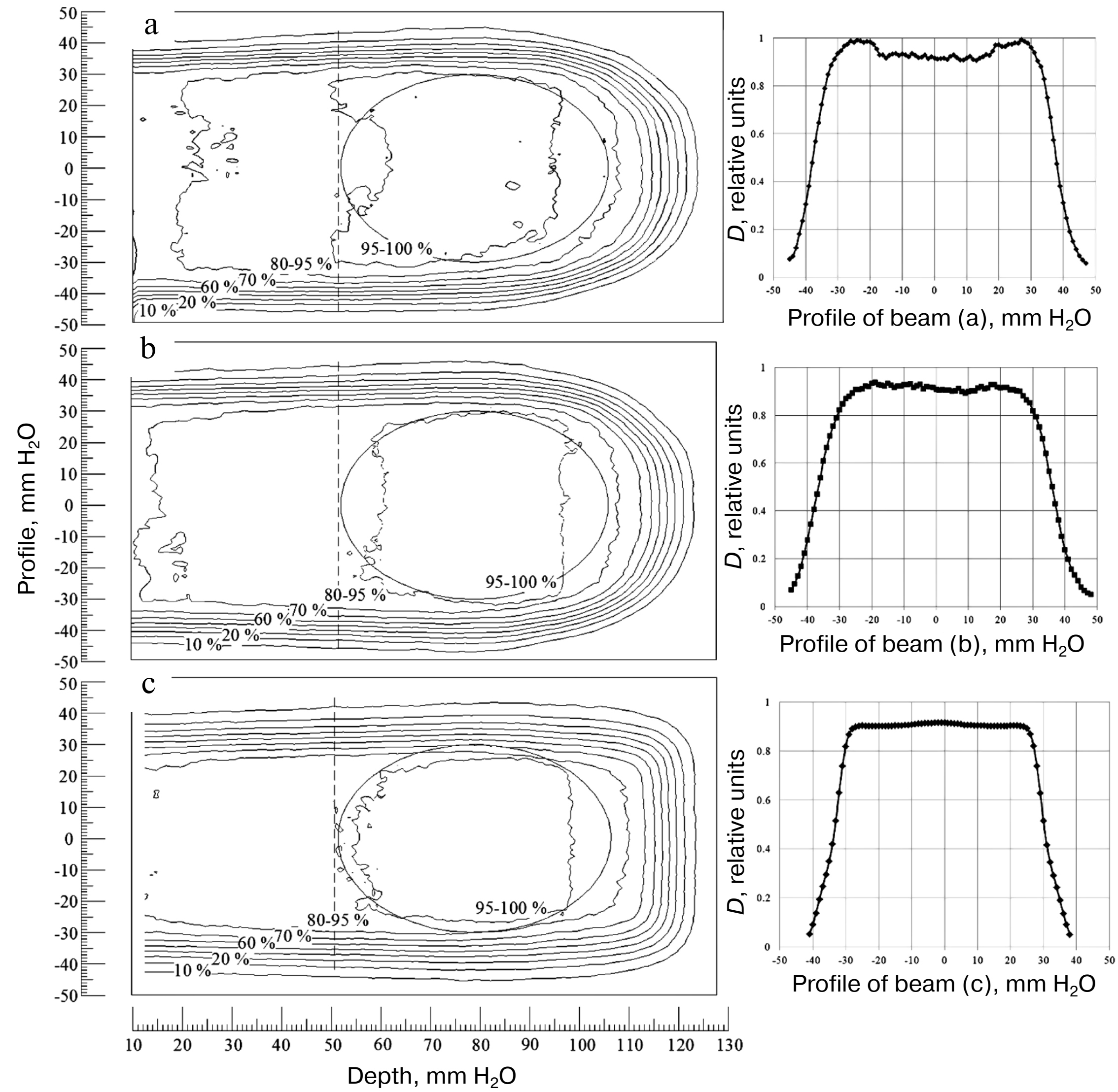


**Fig. 4.** Two-dimensional depth-dose distributions of irradiation of target by three methods (left): a) 3D passive conformal radiotherapy; b) dynamic technique with bolus; c) dynamic technique without bolus. The target outline is shown as a thin line. Transverse beam profiles at the proximal margin of the target are shown on the right (profile plot levels are shown as dotted lines). $D$ — dose in relative units.

level in the median plane of the target across the beam profile was no more than ±5% in all three cases. The distal 20-80% dose drop-off was 1.2 cm for the first distribution, 1.3 cm for the second, and 1.1 cm for the third. Lateral 20-80% dose drop-off in the target area was 0.8 cm for the first distribution, 0.9 cm for the second, and 1 cm for the third.

The third dose distribution for irradiation of the target by the dynamic technique without a bolus contained a dose area at 80-95% beyond the distal margin of the target, pointing to a lower level of conformity than with irradiation methods using a bolus. The lateral and distal dose drop-off gradients were comparable in all three cases and pointed to essentially identical quality of field formation. Distributions obtained using radiochromic films satisfactorily reproduced the planned dose distributions.

## Conclusions

The results of the experimental study confirmed that the dynamic irradiation method developed here eliminates overirradiation tails occurring in the case of standard 3D passive radiotherapy at the MTC and improves the level of conformity for irradiation from a single direction. The dynamic technique simplifies preirradiation preparation for irradiation, as there is no requirement to prepare individually shaped collimators and, in some cases, boluses. Experimental verification also demonstrated the operability of the entire dynamic irradiation system, its accuracy, and the simplicity of its operation.

The variable-thickness automated range shifter and the multileaf collimator developed here are multipurpose devices. Apart from the dynamic irradiation technique, they can also be used in the beam-forming system to implement the standard method of 3D conformal therapy.

Further development of the dynamic irradiation technique at the MTC should involve creating a full-size MLC, additional dosimetric measurements using an anthropomorphic phantom, and introduction of the new technique into the practice of proton radiotherapy.

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