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DEVELOPMENT OF A RADIOTHERAPY SYSTEM BASED ON 6 MeV LINAC AND CONE-BEAM COMPUTER TOMOGRAPH

I. I. Rod'ko,[1] G. A. Sarychev,[1] P. V. Balakirev,[2] T. V. Bondarenko,[2] I. L. Dergacheva,[2] A. S. Evteev,[2] S. N. Kovalev,[2] S. A. Koloskov,[2] T. A. Krylova,[2] T. K. Lobzhanidze,[2] S. A. Polikhov,[2] V. P. Smirnov,[2] G. B. Sharkov,[2] G. E. Gorlachev,[3] I. V. Gulidov,[4] S. A. Ivanov,[4] A. D. Kaprin,[4] Yu. S. Romanko,[4] E. V. Khmelevskii,[4] L. Yu. Ovchinnikova,[5] V. I. Shvedunov,[5] N. V. Shvedunov,[5] and D. V. Cherednichenko[6]

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A system currently under development for remote radiotherapy based on a 6 MeV linac and cone-beam computer tomograph is presented. Its distinguishing design features and solutions are described: compact 5-cm wavelength electron accelerator, solid-state modulator, visualization in the bremsstrahlung beam with low nominal energy 2.5 MeV, bremsstrahlung beam without a compensating filter, cone-beam computer tomography, multi-leaf collimator, adaptive radiotherapy, and a therapeutic table with six degrees of freedom. The system is compared with foreign analogs.

The last few decades have been characterized by complete cessation of the production of home-grown accelerator systems for radiotherapy. In 1997–2002, the serial production of the SL-75-5-MT linear accelerator based on obsolete apparatus from the Philips Company (Netherlands) was organized at the Efremov Research Institute of Electrophysical Apparatus (NIIEFA). In 2008, NIIEFA began to develop a home-grown design of an 6 MeV electron accelerator system. However, the design and fabrication of an experimental sample happened to fall into a difficult period when there was no financial support for this subject area. However, as a result the work could not be fully completed in spite of the team's high professional calibre. The accelerator developed in 2011 has remained in the clinical testing stage and is now obsolete from the standpoint of modern apparatus.

In 2008–2010, oncology clinics, using government support, purchased limited amounts of equipment produced by the Varian (USA) and Elekta (Sweden) Companies. In terms of productivity, this equipment can support the treatment of approximately 60% of the patients requiring it [1]. In addition, expensive routine servicing limits its use. The shortage of 6 MeV electron accelerators in the next five years is estimated to be 250–300 units. These include units that are subject to replacement.

Considering the high demand, a decision was made at the State Corporation Rosatom to develop for remote radiotherapy a 6 MeV electron accelerator, later given the working name KLT-6. This choice of energy was due to the fact that bremsstrahlung beams with nominal energy 6 MeV are used in approximately 70% of the cases. A cooperative of organizations

[1] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia.
[2] Research Institute of Technical Physics and Automation (NIITFA), Moscow, Russia.
[3] Radiation-Oncological Intelligent Systems and Services, Moscow, Russia.
[4] National Medical Research Center of Radiology (NMITS Radiology), Moscow, Russia.
[5] Laboratory of Electron Accelerators (LEU MGU), Lomonosov Moscow State University, Moscow, Russia.
[6] Rusatom Healthcare, Moscow, Russia.

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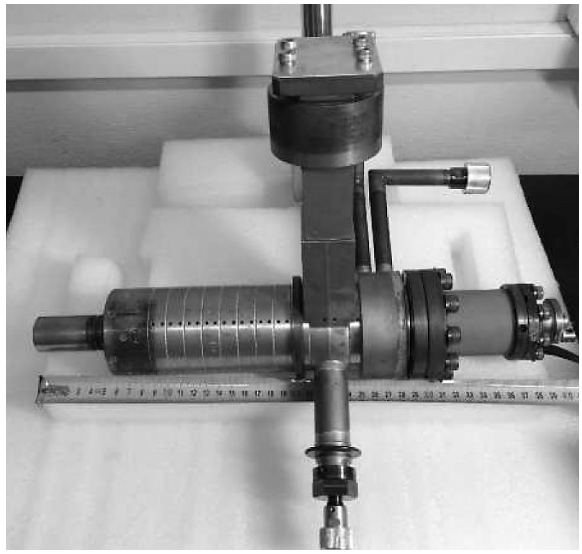

Fig. 1. Five-cm range accelerating structure developed for KLT-6.

Fig. 2. Compact multi-beam klystron.

which is headed by NIITFA was created to develop the design. Several enterprises, including LEU MGU and MIPhI, participated in it. In order to take account of the practical experience of radiotherapists, the national medical research center of radiology was invited into the cooperative. The aim of the project is to develop a system that meets as closely as possible the needs of the radiotherapy departments of clinics and possesses all the capabilities of the leading world-class medical accelerators. Special attention in the design is devoted to acceptable cost and heightened maintainability. A repair service based on an affiliate of NMITsR in Obninsk, where KLT-6 will go through clinical trials, is being created.

System make-up. A radiotherapeutic system for implementing modern procedures of remote radiotherapy is being developed on the basis of a 6 MeV electron accelerator. The bremsstrahlung beam generated by the accelerator can be used with a compensating filter, in which case the maximum radiation dose rate will be 600 cGy/min, or without it, in which case the dose rate increases to 1000 cGy/min. In the the standard configuration, KLT-6 is equipped with a compact 5 cm wavelength range accelerator and a computer tomography system in an x-ray cone-beam [2–4]. The base configuration will make it possible to use the following procedures of radiotherapy: three-dimensional conformal, with modulation of beam intensity, rotational with volumetric modulation of the beam intensity, and a beam procedure using visualization to control the patient's position. Implementation procedures such as beam therapy with synchronization by breathing and adaptive beam therapy will be optional.

TABLE 1. Basic Parameters of KLT-6 in Comparison with Varian (USA) and Electa (Sweden) Linear Accelerators with Nominal Bremsstrahlung Beam Energy 6 MeV in the Base Configuration

Parameter	UNIQUE Performance Edition (Varian) [5]	Compact (Electa) [6, 7]	KLT-6 (NIITFA)
Release date	2012	2008	2021
Power source	Magnetron	Magnetron	Klystron
Maximum radiation dose rate, cGy/min	600	350	600
Beam without compensating filter	No	No	Present, dose rate 1000 cGy/min
Multi-leaf collimator	120 leaves (60 pairs)	No	120 leaves (60 pairs)
Bremsstrahlung with detector:	aS1000 (Varian Medical Systems, USA)	No	IVS (LinaTech, USA–China)
detector matrix resolution, pixels	1024 × 768	No	2688 × 2688
detector active region size, cm	40 × 30	No	41 × 41
Implemented radiotherapy procedures:			
three-dimensional conformal	Yes	Yes	Yes
with beam intensity modulation	Yes	Option	Yes
rotational with volumetric modulation of beam intensity	Yes	No	Yes
Cone-beam computed tomography in x-ray beam:	No	No	Yes
detector matrix resolution, pixels	No	No	3072 × 3072
field of vision, cm	No	No	52
Clearance, cm	43	45	>49

Salient features of KLT-6 are a compact 5 cm range electron accelerator, solid-state modulator, visualization in a bremsstrahlung beam with low nominal energy 2.5 MeV, bremsstrahlung beam without a compensating filter, cone-beam computer tomography, multi-leaf collimator, adaptive radiotherapy, and therapeutic table with six degrees of freedom. The compact and lightweight accelerator design developed at the LEU MGU and its multi-beam klystron will make it possible to reduce significantly the mass and dimensions of the gantry (Fig. 1, 2). The 20-cm long sealed accelerating structure is arranged vertically and does not require a magneto-optic system or additional pumping systems, which increases the stability of the irradiation field, decreases the dimensions and mass of the accelerator, and simplifies operation. The accelerating structure is powered from a KIU-271 multibeam device manufactured by NPP Torii. A consequence of the compactness of the design is a larger free space between the gantry head and the isocenter – the clearance of the accelerator, which makes the positioning of the patient on the KLT-6 therapeutic table during treatment more comfortable (see Table 1). The use of a modern solid-state modulator for the accelerating system will make it possible to generate beams with quickly changeable radiation dose rate, which will make it possible to optimize treatment plans with intensity modulation.

The electron beam energy in the developed the accelerator can be reduced to 2.5 MeV. The corresponding bremsstrahlung beam will be used to obtain higher contrast images of the patient than in the therapeutic beam in order to monitor his position on the accelerator table during an actual therapy session. In the future, cone-beam computer tomography will be implemented in the bremsstrahlung beam. The characteristics of the employed detector are some of the best available at present (see Table 1). Beams without compensating filters are often used to implement radiotherapy procedures with beam intensity modulation and synchronization according to breathing. The high dose rate achieved with such beams decreases the patient's treatment time by 10–30% on average.

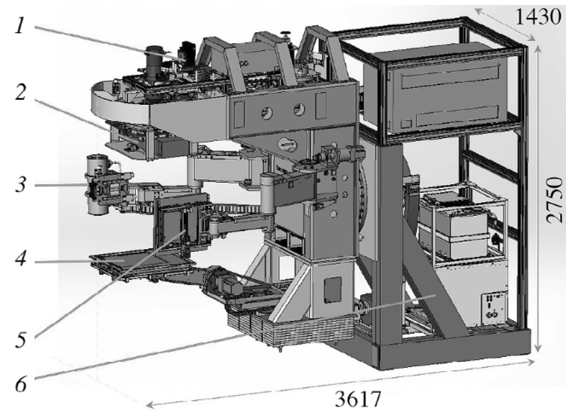

Fig. 3. Contents of the interior units of the KLT-6 system: *1*) gantry with 5 cm wavelength range accelerator; *2*) multi-leaf collimator; *3*, *4*) x-ray tube and x-ray detector of the cone-beam computer tomography system; *5*) bremsstrahlung detector; *6*) mount with solid-state modulator.

The standard KLT-6 configuration will include a cone-beam computed tomography system in an x-ray beam and correspondingly it will support all known x-ray visualization methods for accurate positioning of the patient on the therapeutic table.

The employed collimator with 120 leaves (60 pairs of leaves) makes it possible to produce fields with complicated forms and maximum size to 40 × 40 cm. The width of the central leaves is 0.5 cm and the width of the peripheral leaves is 1 cm. The parameter ‘run-out of leaves beyond the central axis of the beam’ which is significant for implementing radiotherapy procedures with intensity modulation is equal to 20 cm. As an option, the KLT-6 system will be equipped with an automatic adaptive radiotherapy system making it possible to routinely track the change in the size of the irradiated target as well as the closely positioned critical organs and to adjust the treatment plan in strict correspondence with the patient’s current condition. The base procedure will become to use deformable registration algorithms for the contours of the organs at risk and of the targets as well as collections of the patient’s computer-tomography sections obtained with the aid of a cone-beam tomograph.

In its standard configuration, KLT-6 will include a conventional therapeutic table with four degrees of freedom (successive movement along the X, Y, Z axes and isocentric rotation). For more accurate positioning of the patient, the number of degrees of freedom of the table can be increased to six (including the longitudinal slope of the table – the ‘pitch’ and rotation around the patient’s longitudinal axis – the ‘roll’).

The KLT-6 system will have the conventional, for a medical linear accelerator, appearance (Fig. 3). The compact accelerator is arranged coaxially in the gantry (there are no turning magnets). After two pairs of continuous shutters, the beam passes through a specially-developed dose-monitoring system and a multi-leaf collimator. The dose-monitoring system consists of an ionization chamber which monitors the dose released to the patient as well as the dose rate and radiation-beam parameters such as the uniformity and degree of symmetry. If any parameter goes beyond the admissible limits, the system blocks the radiation beam and interrupts the radiotherapy session. An x-ray tube and x-ray detector of the cone-beam computer tomography system are arranged on the drives along the sides of the gantry and a bremsstrahlung detector is arranged at the bottom.

A trial sample of the rotary support system of KLT-6 is now being manufactured at the NPO GKMP (Bryansk). Italian designers are creating the aesthetic appearance of the system. A multi-leaf collimator is being developed and fabricated. Specialized software for controlling the KLT-6 system is being designed. A planning system and an oncological information system, which are mandatory components of modern radio therapeutic system, are being evaluated and chosen. The experimental sample of the KLT-6 system is expected to be assembled at the end of 2019. Additional development of the system and technical testing are planned in 2020 and clinical trials and serial production in 2021, which should meet the domestic market demand for such remote radiotherapy systems and therefore increase accessibility and quality of treatment for oncology patients.

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REFERENCES

1. E. V. Khmelevskii and A. D. Kaprin, “Status of radiotherapeutic work in Russia: comparative analysis and prospects for development,” *Onkologiya. Zh. im. Gertsena*, **6**, No. 4, 38–41 (2017), https://doi.org/10.17116/onkolog 20176438-41.
2. L. Yu. Ovchinnikova and V. I. Shvedunov, “Design of C-band electron linear accelerator for a complex of radiation therapy,” in: *29th Linear Accelerator Conf. LINAC18*, TUPO097 China, Beijing, http://linac2018.vrws.de/papers/tupo097.pdf.
3. D. S. Yurov, L. Yu. Ovchinnikova, A. S. Alimov, et al., “Beam parameters measurement of C-band 6 MeV linear electron accelerator,” *ibid.*, http://linac2018.vrws.de/papers/ mopo061.pdf.
4. A. N. Ermakov, A. S. Alimov, L. Yu. Ovchinnikova, et al., “Linacs for industry, cargo inspection and medicine designed by Moscow University,” *ibid.*, http://linac2018.vrws.de/papers/mopo060.pdf.
5. *UNIQUE™ . The Complete Radiation Oncology Solution. Specifications*, VEO OS 1050I, Varian Med. Syst. Int. AG, Cham, Switzerland (2016).
6. *Elekta Compact™. Product Data*, Art. No. 4513 371 0755, Elekta AB, Stockholm, Sweden.
7. *Elekta Compact™. Site Planning Guide*, No. 1005521 03, Elekta AB, Stockholm, Sweden, 11/2010.