Clinical Oncology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Clinical Oncology

journal homepage: www.clinicaloncologyonline.net

Editorial

Developing Innovative, Robust and Affordable Medical Linear Accelerators for Challenging Environments

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Received 22 October 2018; accepted 15 January 2019

The annual global incidence of cancer is projected to rise in 2035 to 25 million cases (13 million deaths), with 70% occurring in low- and middle-income countries (LMICs), where there is a severe shortfall in the availability of radiotherapy [1] – an essential component of overall curative and palliative cancer care. A 2015 report by the Global Task Force on Radiotherapy for Cancer Control estimated that by 2035 at least 5000 additional megavolt treatment machines would be needed to meet LMIC demands, together with about 30 000 radiation oncologists, 22 000 medical physicists and 80 000 radiation therapy technologists [2]. Among the main reasons for the shortfall identified in the workshop and thoroughly discussed in the *Clinical Oncology* special issue on radiotherapy in LMICs [3] are: (i) the initial cost of linear accelerators, (ii) the cost of service on the machines and (iii) a shortage of trained personnel needed to deliver safe, effective and high-quality treatment. A number of authors who contributed to the *Clinical Oncology* special issue are participating in the CERN, International Cancer Expert Corps (ICEC), Science and Technology Facilities Council (STFC) collaborative effort described in this editorial (Aggarwal, Coleman, Court, Grover, Palta, Van Dyk and Zubizarreta).

Taking Action

Motivated by these factors and the sustainable development goals of the United Nations [4], two multidisciplinary

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https://doi.org/10.1016/j.clon.2019.02.002

international workshops were hosted by CERN [5,6]: Design Characteristics of a Novel Linear Accelerator for Challenging Environments, November 2016, sponsored by the ICEC [7] and Innovative, Robust and Affordable Medical Linear Accelerators for Challenging Environments, October 2017, sponsored by ICEC and the UK STFC. Recommendations from the latter workshop are the focus of this paper and were reviewed at a workshop in the UK in March 2018: Burying the Complexity: Re-engineering for the Next Generation of Medical Linear Accelerators for Use in Challenging Environments, hosted by STFC in collaboration with CERN and ICEC. The goals of the workshops were to brainstorm regarding the shortfalls in care from the perspective of linac users in UK Overseas Development Assistance (ODA) countries and to initiate planning to develop an innovative, robust (environmentally tolerant) and affordable low-cost linac with IT-based solutions for treatment planning and quality assurance for use primarily in resource-poor settings. The workshop attendees were a multidisciplinary group of international experts in accelerator physics, detector physics, medical physics, biology, radiation and clinical oncology, epidemiology and global cancer policy.

A great many of the challenges in delivering radiotherapy in LMICs that were pointed out by Barton *et al.* [8], Yap *et al.* [9] and Zubizarreta *et al.* [10] in the *Clinical Oncology* special issue on radiotherapy in LMICs [3], were further detailed during the workshop by those working 'on the ground' in LMICs. There is: (i) a shortage of good-quality radiotherapy equipment capable of both simple and more complex radiotherapy treatment delivery, (ii) the challenge of servicing the linacs, both for preventative maintenance and upon equipment breakdown and (iii) the chronic shortage of adequately trained personnel. In LMICs, the costs of equipment, building and salaries are 81, 9 and 10% of the total cost of the facility, respectively, compared with 30, 6 and 64% in high-income countries [2]. Healy *et al.* [11] point out that infrastructure and maintenance are more demanding for current linacs as are the needs for staffing and staff training. These limitations and that there has been no change in the design of megavoltage machines for 50 years, as pointed out by Barton *et al.* [8] are why the CERN, ICEC, STFC collaboration is looking at innovative solutions for a robust, modular and affordable linac and radiation therapy treatment system for challenging environments. There are substantial opportunities for scientific and technical advancement in the design of the linac and the overall operation of the radiation therapy treatment system for LMICs, some of which are provided below.

Radiofrequency Power Systems

To get a better understanding of the performance of radiofrequency power systems, the characteristics of klystron and magnetron radiofrequency sources in terms of cost, reliability and complexity as a function of radiofrequency frequency and power delivery levels are being investigated. Additional studies are evaluating, the performance of solid-state radiofrequency power supply systems with regard to their cost and the possibility of modularity to improve efficiency and servicing without requiring termination of operation of the whole system.

A detailed comparison of solid-state power amplifiers and vacuum tube amplifiers as well as the possible role of the recently reported development of compact multi-beam klystron technologies is being carried out.

The relative merits, specifications and applicability of S-band, C-band and X-band standing wave and travelling wave accelerator waveguides are being evaluated in the context of implementation constraints, which typically exist in ODA countries, such as electricity provision, cooling stability, high humidity and associated environmental challenges.

Durable and Sustainable Power Supplies

Operational experience with modern medical linacs was reviewed to include control systems, cooling requirements of various subsystems, stability of operation as well as servicing and costs associated with these features. To make radiation therapy treatment equipment broadly available in ODA countries, as well as in other countries with similar environments, it is necessary to simplify the machine and its control system while improving the overall quality of all of its components. It would be especially important to reduce the number of energy-dependent components, such as vacuum pumps, electromagnets and diagnostics. Increasing the number of passive components used in the future machine is advisable considering possible challenges in accessing clean water and stable energy. A control system that enables remote component failure evaluation and prediction of service needs is essential to minimise machine downtime for servicing.

An important design goal of the 'novel' medical linac is modularity. Such functionality allows system upgrades from a basic functional configuration to provide adequate treatment to be delivered almost immediately while transitioning to the level of sophistication needed to deliver complex radiotherapy to optimise tumour control and minimise side-effects, such as with intensity-modulated radiotherapy, which requires multileaf collimators. This feature of modularity and the potential to upgrade treatment capability provides an incentive for continued education and can create a stimulating work environment that is important for retaining in-country highly skilled and well-trained people. By starting with a basic functional configuration, this concept would allow much of the maintenance of the equipment to be carried out by trained local personnel rather than manufacturer's specialists, thereby resulting in far fewer and shorter delays due to breakdowns.

Linac Beam Production and Control

The essential elements of a linac include beam energy, average beam current and beam size on the X-ray target. It was agreed that ideally a single electron beam energy between 6 and 10 MeV should be made available to avoid activation of materials that would minimise unnecessary background radiation, thereby reducing the extent of shielding needed, the

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servicing costs and the overall mass of the machine. The overall full-width-half-maximum (FWHM) of the electron beam diameter on the target needs to be kept below 2.0 mm.

Other essential elements are beam production, acceleration, beam transport, collimation, diagnostics, vacuum and control requirements. Comparing complexities of construction and maintenance of different beam emitting cathodes led to the recommendation to use a thermionic cathode. The diode or triode electron gun design based on a thermionic emission cathode is suitable to deliver the required beam current. Because the gun is an integral part of the accelerating structure, the reliability and cathode lifetime are important for robust operation. It is important to deliver a beam to the target with minimum losses to avoid generation of X-rays prior to the target. Such an ambient X-ray field increases the radiation dose load of the patient and can potentially damage unprotected electronics. This can be avoided by applying collimation while the beam has low energy and by using magnets at high energy to transport the beam to the target. For a single-energy radiation therapy system, permanent magnets could be used to reduce the complexity in terms of electrical supply and water cooling. Electron beam rastering and scanning over the target was considered against the simplified multileaf collimators system but these are potentially more complex and risky options.

Linac Safety and Operability

Key operational features of linacs include integrated safety and quality assurance subsystems, including ion chambers, feedback controls and safety interlocks. Other critical features are simplified controls with diagnostics for remote operation, remote control and monitoring and the possibility of integrated shielding with low leakage and optimised systems to improve portability. Engineering challenges include coupling existing trends in computing, sensors and readout systems; avoiding complex custom electronics; keeping systems as standard as possible; using a network of fault-tolerant sensors as well as a single low-cost platform for data acquisition and data processing. These research efforts and those mentioned below are part of the overall quality assurance system described by Meghzifene [12].

Inherent in operational safety are interlock systems that integrate operation of the linac with the movement of the gantry, the treatment couch and the patient. Feedback systems for dose control should use highly fault-tolerant programmable logic that is robust against hardware faults. Improvements to ion chambers or more reliable failure-tolerant detectors of a different type are needed. Validation of programmable systems is another critical safety feature. With regard to improved internal shielding, codes exist that can be rapidly adapted to new shielding configurations, thereby allowing simulation of the entire machine to determine the locations of radiation losses. Machine operator performance might be improved by machine learning approaches to completely simulate the accelerator system for virtual (augmented) reality training, commissioning and acceptance testing of the treatment system.

Computer Applications in Radiation Therapy

In the *Clinical Oncology* special issue on radiotherapy in LMICs [3], Feain *et al.* [13] describe several computer-based initiatives to improve the planning, delivery and quality assurance of radiotherapy in LMICs. Two of the authors (Court and Palta) are participating in the project described in this editorial. Among the many opportunities to reduce the possibility of computer errors in the design of software for radiotherapy applications is automated monitoring of treatment delivery by record and verify systems. This is but one component of a complete radiotherapy information management system that: (i) can interface with imaging systems, (ii) is capable of scheduling and data analytics, (iii) can provide dose alert functionality and (iv) can facilitate administrative functions such as image archiving and record keeping. Other examples include:

(1) A cloud-based medical informatics infrastructure to support the delivery of high-quality radiotherapy-based cancer treatment in developing countries by strengthening the training of a multidisciplinary healthcare work force was described [14]. This infrastructure platform provides a knowledge-sharing portal by enabling peer review of treatment plans, facilitates twinning partnerships within or between countries and enables remote radiation therapy quality assurance to enable international research trial participation.
(2) The Radiation Planning Assistant, which is an automated contouring and treatment planning system, is designed to reduce the time a physicist or dosimetrist spends doing treatment planning as well as to limit the need for the radiation oncologist to delineate the target volume, provide the treatment prescription and approve the plan [15].
(3) A software program has been designed to teach linac physics through simulation that relates basic physical principles to clinical parameters using simple analytics [16]. This was designed to address the lack of availability of clinical linacs for teaching physicists, medical physicists and service engineers. The program simulates the service mode of operation with a response that is consistent with that of a real clinical linac.

CERN's openlab [17] illustrates how a collaborative space that can evaluate and test state-of-the-art technologies in collaboration with industry and other communities can be a useful tool.

Following on from this meeting, funding was provided by the UK STFC to investigate five recommendations from the workshop for the next steps in the linac project:

- Evaluate radiofrequency power systems and optimised radiofrequency structures for electron beam acceleration

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- Evaluate robust permanent magnet beam delivery systems for medical radiotherapy linac
- Study optional accelerator technologies
- Study linac simulations to determine stable and sustainable operating conditions for radiotherapy linacs in challenging environments
- Develop cloud-based electronic infrastructure for support of linac-based radiotherapy in challenging environments

The results of these work packages and other ongoing efforts by the ICEC will form the basis for programmatic and network funding to support the design and development of a fully integrated radiotherapy treatment machine and radiotherapy planning system for use in low-resource settings that face challenges in upscaling their radiotherapy infrastructure to meet increased demand.

Summary

This unique multidisciplinary collaboration on innovative technology involving CERN, ICEC and STFC included high-energy accelerator physicists, medical physicists, clinical and radiation oncologists, health policy and epidemiological scientists as well as medical physicists and clinical oncologists from ODA countries. The five technical research topics defined and outlined here provide a foundation for the potential design of an innovative linac and associated radiation therapy treatment system that will enhance the capability and reduce the complexity of treating patients with radiotherapy in ODA countries. Likewise, the innovative linac and radiation therapy treatment system should be of interest to radiation oncologists in resource-rich countries that have geographically isolated communities, often indigenous populations, who could also benefit from this innovative technology. In keeping with the need for education and training pointed out by Barton *et al.* [8] and by Eriksen [18] there is a parallel effort by ICEC to address the shortage in cancer care for the underserved worldwide that focuses on mentorship, education and ongoing training.

Conflict of Interest

The authors declare no conflict of interest

Acknowledgement

Much of the information in this editorial was the result of a workshop at CERN in October 2017 that made further progress in addressing the need for global cancer care. The workshop would not have been possible without CERN's generosity in hosting the workshop and support from the STFC and the ICEC. Funding for travel by ODA country personnel as well as STFC invitees and for workshop logistics was provided by STFC. No funds were provided from the National Institutes of Health (NIH). C. Norman Coleman is employed by the NIH. However, for him, this is a formal outside activity unrelated to NIH employment.

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