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Original Article

Surveying the Challenges to Improve Linear Accelerator-based Radiation Therapy in Africa: a Unique Collaborative Platform of All 28 African Countries Offering Such Treatment

T.A. Ige [*,†], A. Jenkins [‡], G. Burt [§], D. Angal-Kalinin [¶], P. McIntosh [¶], C.N. Coleman [||], D.A. Pistenmaa [||], D. O'Brien [||], M. Dosanjh [‡,||,**]

[*] National Hospital Abuja, Abuja, Nigeria
[†] University of Abuja, Abuja, Nigeria
[‡] University of Oxford, Oxford, UK
[§] University of Lancaster, Lancaster, UK
[¶] STFC Daresbury Laboratory, Warrington, UK
[||] International Cancer Expert Corps, Washington, DC, USA
[**] CERN, Geneva, Switzerland

Abstract

Radiation therapy is a critical component for curative and palliative treatment of cancer and is used in more than half of all patients with cancer. Yet there is a global shortage of access to this treatment, especially in Sub-Saharan Africa, where there is a shortage of technical staff as well as equipment. Linear accelerators (LINACs) offer state-of-the-art treatment, but this technology is expensive to acquire, operate and service, especially for low- and middle-income countries (LMICs), and often their harsh environment negatively affects the performance of LINACs, causing downtime.

A global initiative was launched in 2016 to address the technology and system barriers to providing radiation therapy in LMICs through the development of a novel LINAC-based radiation therapy system designed for their challenging environments. As the LINAC prototype design phase progressed, it was recognised that additional information was needed from LMICs on the performance of LINAC components, on variables that may influence machine performance and their association, if any, with equipment downtime. Thus, a survey was developed to collect these data from all countries in Africa that have LINAC-based radiation therapy facilities. In order to understand the extent to which these performance factors are the same or different in high-income countries, facilities in Canada, Switzerland, the UK and the USA were invited to participate in the survey, as was Jordan, a middle-income country. Throughout this process, LMIC representatives have provided input on technology challenges in their respective countries.

This report presents the method used to conduct this multilevel study of the macro- and microenvironments, the organisation of departments, the technology, the training and the service models that will provide input into the design of a LINAC prototype for a LINAC-based radiation therapy system that will improve access to radiation therapy and thus improve cancer treatment outcomes. It is important to note that new technology should be introduced in a contextual manner so as not to disrupt existing health systems inadvertently, especially with regards to existing staffing, infrastructure and socioeconomic issues. A detailed analysis of data is underway and will be presented in a follow-up report. Selected preliminary results of the study are the observation that LINAC-based facilities in LMICs experience downtime associated with failures in multileaf collimators and vacuum pumps, as well as power instability. Also, that there is a strong association of gross national product per capita with the number of LINACs per population.

Key words: Access to radiation therapy; barriers to cancer care in LMICs; cancer care in LMICs; global health; linear accelerator technology

Introduction

Radiation therapy is a critical component for the curative and palliative treatment of cancer and is considered to be a necessary component of treatment for over half of all cancer patients [1]. There is, however, a global shortage and disparity in the access to radiation therapy, leaving a

Author for correspondence: M. Dosanjh, International Cancer Expert Corps, 1608 Rhode Island Ave NW Suite 243, Washington, DC 20036, USA. Tel: +41-75-411-47-25.

E-mail address: manjit.dosanjh@cern.ch (M. Dosanjh).

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tremendous void in the multidisciplinary care of cancer patients, especially for patients with advanced cancers for whom treatment with both chemotherapy and radiotherapy is indicated. In recent reports, only 10–40% of the approximately 4.0 million cancer patients annually in low- and middle-income countries (LMICs) who required radiation therapy were able to access such treatment [2–5]. With many LMICs having inadequate or, in many cases, no radiation therapy centres, it is projected that about 12 600 radiation therapy machines will be needed globally over the next two to three decades to meet the demand in LMICs [6,7].

Many LMICs provide radiation therapy using cobalt-60 technology because these treatment units are generally less expensive than linear accelerators (LINACs), are less dependent upon local infrastructure and are easier to operate and maintain. Current cobalt-60 machines incorporate multileaf collimators that improve the efficacy of treatment with fewer adverse effects. However, the greater depth-dose penetration of X-ray beams from LINACs can decrease the adverse effects of treatment relative to cobalt-60 machines, even with comparable treatment techniques. LINACs are preferred by radiation oncologists in clinical situations where the technical capabilities to deliver complex treatments may be beneficial, but the dilemma exists in LMICs because current LINACs are significantly more expensive, complex and labour-intensive to operate and maintain than cobalt-60 machines. However, the expense of radioactive source replacement and disposal, in addition to the reduced treatment capacity due to increased treatment time per patient as the source decays are now being better appreciated in the overall cost of operation of cobalt-60 machines. As pointed out by Healy *et al.* [8], these technical factors that pose particular challenges in LMICs must be considered in terms of the complex economic, physical infrastructure, societal priorities and workforce shortages that can influence the ability of these countries to provide cancer treatment using LINAC-based radiation therapy technology in lieu of or in addition to treatment with cobalt-60 machines [7]. An unrelated concern about cobalt-60 machines is the potential terrorist risks posed by the radioactive material in cobalt-60 machines [9]. This is of special concern in selected regions of Africa where there is significant terrorist activity.

Recognising that addressing the barriers to providing LINAC-based radiation therapy in LMICs would require multilevel global collaborative strategies, including public–private partnerships, multidisciplinary collaboration, industry partnerships, innovative strategies and support from healthcare systems and governments, the International Cancer Expert Corps (ICEC) sponsored an international workshop hosted by CERN in Geneva in 2016. Participants included experts from the fields of oncology, accelerator physics and healthcare, as well as representatives from industry and government-funded science institutes from around the world [10–12]. In addition to confirming the shortage of LINACs (and associated software packages that constitute a radiation therapy system) in LMICs, the workshop identified a significant shortage of adequately trained personnel at all levels of responsibility, as noted by Barton *et al.* [3] and Eriksen [13]. The need for postgraduate education in radiation oncology and considerations in providing it in LMICs are also presented by Eriksen [13]. Other specific challenges to overcome in LMICs are a lack of resources for investment in healthcare, environmental conditions that affect the performance of sophisticated radiation therapy technology (power, electricity, clean water), insufficient space to house new equipment, the cost of the technology and the shielded facility and the high cost of servicing and maintaining LINACs. Taking into account all of the above issues, it is therefore important to introduce new technology in a contextual manner recognising the possible impact on existing staffing, infrastructure and socioeconomic conditions.

The ongoing collaboration established at this workshop includes personnel from ICEC, CERN, the UK Science and Technology Facilities Council, Lancaster University and the University of Oxford. They have been joined in this effort by experts representing several LMICs. All participants have a common goal of developing an affordable and high-quality LINAC-based radiation therapy systems solution for challenging environments based on recognition that there are substantial opportunities for scientific and technical advancement in the design of the LINAC and the associated elements of a radiation therapy system. These considerations have been discussed and debated in several subsequent design workshops that included LMIC stakeholders [14–16]. The results of the subject survey will benefit the funded ITAR (Innovative Technologies towards building Affordable and equitable global Radiotherapy capacity) initiative by providing critical information on persistent shortfalls in basic facility infrastructure, radiation therapy equipment and the specialist workforce [17,18]. Some of the opportunities to improve LINAC design that are being explored include: extending the life of LINAC subsystem components, making components easier to replace, reducing the dependency on highly trained internal staff or external service personnel to avoid associated delays in the repair of equipment and minimising the impact of a highly variable electricity supply. Another survey that is nearing completion is designed to assess current general staffing levels in 28 African countries that provide LINAC-based radiation therapy. It will be reported separately.

The absence of detailed statistical data regarding the exact effects that challenging LMIC environmental factors have on LINAC downtime and failure modes presents a critical barrier in determining design features to improve the performance of current LINAC technology. A limited LINAC-based study looking at barriers to providing radiation therapy services by facilities in Gaborone, Botswana and Abuja, Nigeria compared with Oxford, UK was conducted in 2018 by Wroe *et al.* [19]. They reviewed the equipment maintenance logs of LINACs in single locations in each of the three countries [19]. Later, at a technical design workshop held in Washington DC in 2019, it was determined that the ongoing design and prototyping process required more detailed and comprehensive information on equipment failures, maintenance and service shortcomings, personnel, training, country-specific healthcare challenges, etc. from a much larger representation of LMICs. That decision led to the survey that is the subject of this article, namely a study to collect data to make better-informed decisions on the re-engineering needed to produce a novel, robust, modular and more effective LINAC for use in LMIC environments.

Materials and Methods

Data collection in high-income (HICs) and middle-income countries (MICs) is relatively straightforward. However, in LMICs it is a substantial effort to build the trusted partnerships, collect initial data and further refine data collection and analysis within newly formed collaborations. The few existing data sets regarding the average number and types of radiation therapy units in African countries provide mainly high-level data [1–5,20–23]. What is needed is more data from the radiation oncologists and medical physicists in LMICs who use LINAC technology and who can provide the detailed information required to improve radiation therapy technology. Unfortunately, there is commonly a lack of these resources to gather data in African countries and in other LMICs because such surveys are limited by the extent of participation. That the painstaking work required to secure the commitment of a network of experts in LMICs – already facing overwhelming challenges to provide treatment to cancer patients – is based on trust and a sense of common purpose is well known to those working in global health [24–27]. The inclusion of LMIC representatives was central to this project from its inception. Strong relationships were established around a common goal.

In a few months we succeeded in securing the commitment of radiation oncologists and medical physicists from radiation therapy facilities in all 28 countries in Africa that have LINAC-based radiation therapy (Figure 1) to participate in the survey and have obtained preliminary data. We believe that the level of co-operation of the oncologists and medical physicists in the future has been enhanced by recognising them as co-authors on a book chapter in 'Approaching global oncology: the win–win model' related to this survey and in the acknowledgment to this article (also see supplementary Table S1). Through their interest and commitment, the oncologists and medical physicists from the 28 African countries have created a platform suitable for subsequent collaborative efforts through which further details on possible LINAC design changes to overcome environmental and other challenges to radiation therapy delivery in LMICs can be determined and, equally important, can address issues of staffing and staff training,

Fig 1. Map showing the location of all 28 African countries with linear accelerator (LINAC)-based radiation therapy that responded to the survey. Countries that are not shaded do not have LINAC-based radiation therapy.

as well as problem solving by way of ancillary technological improvements through artificial intelligence and machine learning. Another area for future investigation – and ultimately implementation of improved treatment capacity and capability – is to obtain data on the type, stage and incidence of the various cancers in the participating countries. These data will contribute to a much better radiation therapy system that will improve access to radiation therapy equitably for patients with cancer in all countries in Africa as well as to patients globally.

Scores of cancer providers and medical physicists interested in improving access to and the quality of cancer care globally have been involved from the outset of this project in 2016 to develop a better LINAC and the rest of the radiation therapy system. With input from stakeholders, a survey questionnaire was constructed to obtain maximum information to define design parameters to improve access to LINAC-based radiation therapy in LMICs (see supplementary Table S2). The survey questionnaire was sent by one of the authors (TAI) to the designated facilities in the 28 African countries by personal communication. As shown in Table 1, which summarises the questionnaire, the survey includes questions related to macroenvironmental metrics among the 28 African countries with LINACs (see Figure 1) related to the structure of and investment in healthcare systems, investment in infrastructure and economic capacity that influence access to radiation therapy [1–5,28–30]. Because of these variations in settings across the LMICs, the detailed analysis will examine factors for each country in the macroenvironment section of Table 1. In addition to differences described above that influence access to radiation therapy [1,2], there are also differences among countries in cancer incidence, including the top three cancer types for which treatment with radiation therapy is needed [2,5,21–23].

Microenvironmental metrics being surveyed and analysed (see Table 1) include for each facility: (i) LINAC manufacturer, model and age; (ii) facility environment (e.g. humidity and room temperature); (iii) reliability of electrical power; (iv) availability of equipment service and maintenance; (v) critical LINAC subsystem information such as radiation production, electromechanical collimation of the X-ray beam, power consumption and heat dissipation; and (f) safety as well as information on diagnostic imaging, treatment capability, training and technical support. Understanding how these conditions affect access to LINAC technology, especially downtime, in LMICs compared with HICs has not been studied extensively [19]. Therefore, a comparison with HIC facilities in the USA, Switzerland, the UK and Canada, as well as a facility in Jordan, a MIC, was added to the current survey. As expected, data are more readily available from facilities in HICs by way of providers and professional societies.

Results

Comparative Data on Linear Accelerator Access

Preliminary data developed by ICEC showing the marked variation in LINAC-based radiation therapy capacity (the number of people served by each LINAC) across the continent of Africa is presented in Table 2 and also shown graphically in Figure 2. There are varying benchmarks for the recommended number of radiation therapy units per

Table 1
Selected metrics by country and the data sources used in the survey

Level	Metric by country	Data source [reference]
Macroenvironment	World bank classification	World Bank
	GNP per capita	World Bank [24]
	Population	UN [25]
	Number of LINACs	IAEA DIRAC [15]
	Average temperature and precipitation	World Bank [26]
	Power outages by country	World Bank [26]
	Cancer incidence	WHO
	Top three cancer types	WHO
Microenvironment	Space dimensions and shielding	Survey
Healthcare organisation	Room temperature and humidity	Survey
	Internet reliability	Survey
	Power stability	Survey
	Water quality	Survey
	Utilisation – patient volume	Survey
Technology performance support	Staff expertise	Survey
	Local maintenance capability	Survey
	Service contract	Survey
	Availability of spare parts	Survey
Technology	Manufacturer	Survey
	Model	Survey
	Age	Survey
	Ancillary features (imaging, couch)	Survey

GNP, gross national product; IAEA DIRAC, International Atomic Energy Agency Directory of Radiotherapy Centres; LINAC, linear accelerator; WHO, World Health Organization.

Table 2
Access to radiation therapy in 28 African countries with linear accelerators (LINACs) compared with access in one middle-income country (Jordan) and four high-income countries shown in order of best access to radiation therapy (most LINACs per population) to poorest access to radiation therapy (fewest LINACs per population)

Country	Population in millions	Population/ machine	Radiation therapy units in use	Radiation therapy units needed	Radiation therapy capacity (%)
USA	331	87 000	3827	1655	231.2
Switzerland	8.6	119 000	72	43	167.4
Canada	37.6	132 400	284	197	144.2
UK	67.9	195 000	348	340	102.4
Jordan	9.9	762 000	12	50	26
28 African countries with LINACs					
Mauritius	1.27	423 000	3	6	50.0
Tunisia	11.7	509 000	23	58	39.7
South Africa	59	608 000	97	295	32.9
Egypt	102	857 000	119	510	23.3
Morocco	36.9	880 000	42	184	22.8
Gabon	2.2	1.1 million	2	11	18.2
Libya	6.9	1.15 million	6	34	17.6
Algeria	43.8	1.18 million	37	219	16.9
Namibia	2.5	1.25 million	2	12	16.7
Zimbabwe	14.8	2.1 million	7	74	9.5
Botswana	2.3	2.3 million	1	11	9.1
Mauritania	4.6	2.3 million	2	23	8.7
Kenya	53.8	4.89 million	11	269	4.1
Rwanda	10.5	5.25 million	2	52	3.8
Senegal	16.3	5.43 million	3	81	3.7
Sudan	43.9	5.49 million	8	219	3.7
Zambia	17.9	6 million	3	89	3.4
Ghana	31.0	7.75 million	4	155	2.6
Angola	32.9	11 million	3	164	1.8
Tanzania	59.7	11.9 million	5	298	1.7
Cote d'Ivoire	26.4	13.2 million	2	132	1.5
Madagascar	27.7	13.85 million	2	138	1.4
Mali	20.2	20.2 million	1	101	1.0
Nigeria	206	29.4 million	7	1027	0.7
Cameroon	26.5	26.5 million	1	132	0.8
Mozambique	31.2	31.2 million	1	156	0.6
Uganda	45.7	45.7 million	1	228	0.4
Ethiopia	115	115 million	1	575	0.2

population. For this article, the number of radiation therapy units needed and the radiation therapy capacity in Table 2 are based on the International Atomic Energy Agency recommendation of one radiation therapy unit per 200 000 population [20]. Although 28 African countries have LINAC-based radiation therapy facilities, 27 other African countries, unfortunately, have no LINAC-based radiation therapy facilities whatsoever. The majority of LINACs in Africa are found in the Mediterranean countries (227) and in South Africa (97) [20]. The lack of radiation therapy capacity is especially pronounced in the Sub-Saharan region, where most of the 27 countries that do not have LINAC-based radiation therapy are located. Unfortunately, almost all of the countries in the Sub-Saharan region that do have LINACs have very few such machines in proportion to their populations. The ratio of the number of machines to people in the 28 countries with LINAC-based radiation therapy facilities ranges from one machine to 423 000 people in Mauritius, one machine to almost 5 million people in Kenya [20] and one machine to over 100 million people in Ethiopia. In comparison, in HICs, such as the USA, Switzerland, Canada and the UK, the ratio is one radiation therapy machine to 87 000, 119 000, 134 000 and 195 000 people, respectively. Jordan has a ratio of one radiation therapy machine to 762 000 people [20]. To draw a stark comparison, Africa has about one LINAC per 3 million people, whereas the USA has one LINAC per 87 000 people, a factor of 35 [20].

Ongoing Analysis

At this point in the data collection and analysis, there are 100 LINACs in the two arms of the study representing a number of manufacturers. It is not the intent of this effort to compare the equipment by manufacturer but rather to address the commonality of problems in infrastructure and in the radiation therapy systems that will provide information to produce effective design solutions. The data will

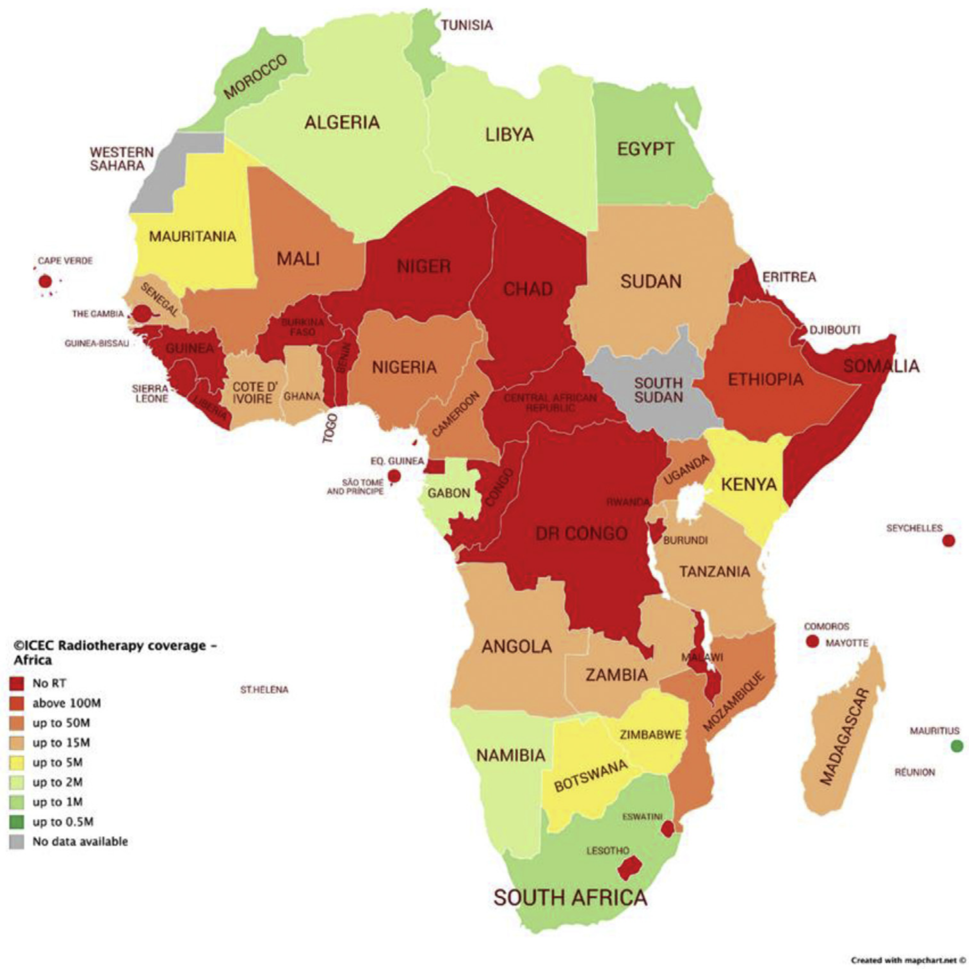

Fig 2. Graphic representation of preliminary data developed by the International Cancer Expert Corps (ICEC) that shows the marked variation across Africa in linear accelerator (LINAC)-based radiation therapy capacity (the number of people served by each LINAC).

allow for the determination of those characteristics of LINACs and radiation treatment procedures that can be improved by technology (hardware and software) in order to enhance the capability and capacity of LMIC facilities to treat cancer patients. The ongoing detailed multilevel and multivariate analyses of the data obtained in the survey will be used to assess the relationship between each data variable and LINAC downtime. In addition to information related to survey variables that affect the performance of LINACs, our analysis includes data related to the level of resources of each country in terms of gross national product (GNP) per capita and the number of LINACs per country population. GNP per capita is generally associated with the extent of healthcare infrastructure and investment [28–30]. Because of these variations in settings across the LMICs, this study also analyses factors for each country in the macro-environment section of Table 1.

Of interest, our initial analysis shows a strong association of GNP per capita with the number of inhabitants per radiation therapy machine, consistent with this relationship shown in other studies [1–5,28–30]. The countries in Africa with LINAC-based radiation therapy facilities fall into two clusters, as shown in Figure 3. The countries in Sub-Saharan Africa principally constitute the cluster with the poorest access to radiation therapy (upper left). The cluster of HICs shown in the lower right of Figure 3 have high GNPs per capita and the greatest access to radiation therapy. The cluster in between shows a strong representation of northern African countries that generally have higher GNPs per capita. Jordan falls in the favourable (right) side of the middle group.

Among the microenvironmental findings regarding technology reported by the radiation therapy facilities in the 28 African countries that have LINACs are that downtime appears to be associated with vacuum pump and multileaf collimator failures as well as power instability. This is consistent with the previous findings of Wroe *et al.* [19]. Thus, minimising the frequency of vacuum pump failures is a major factor for consideration in the design of LINACs specifically for LMIC settings in conjunction with recommending improvements in preventive maintenance programmes. Further analysis will provide information on how these and other equipment failures are managed, such as by maintaining spares for selected components, having staff expertise or contracts for servicing LINACs and the extent to which these measures influence downtime. Overall, the operational reliability of LINACs as solicited by

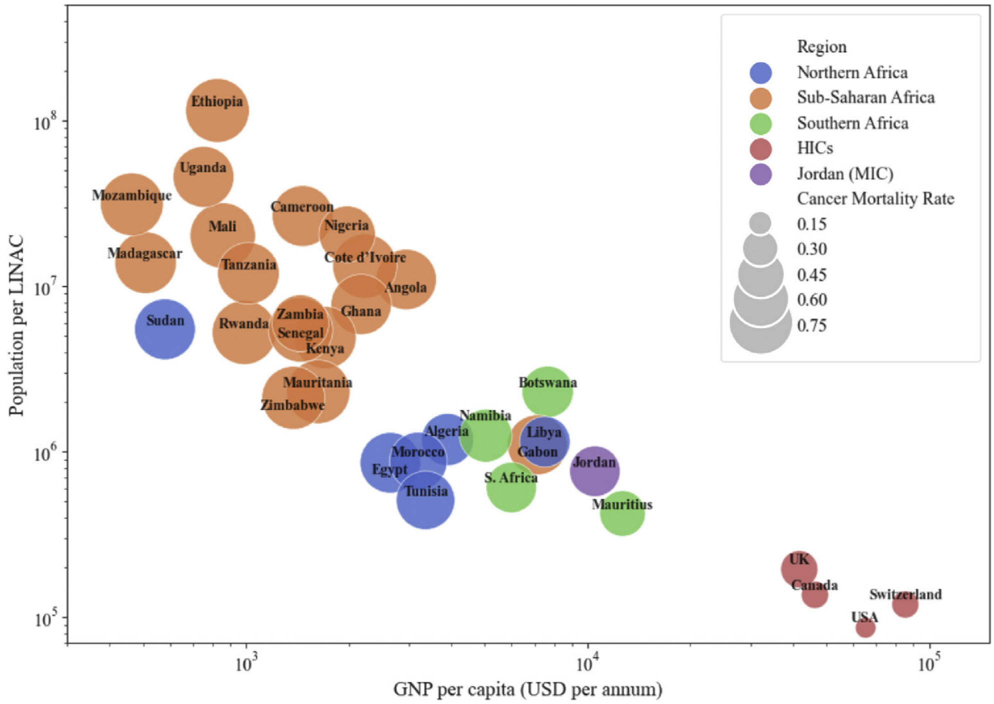

Fig 3. Countries in the study plotted graphically by gross national product (GNP) per capita and the ratio of inhabitants to radiation therapy machines.

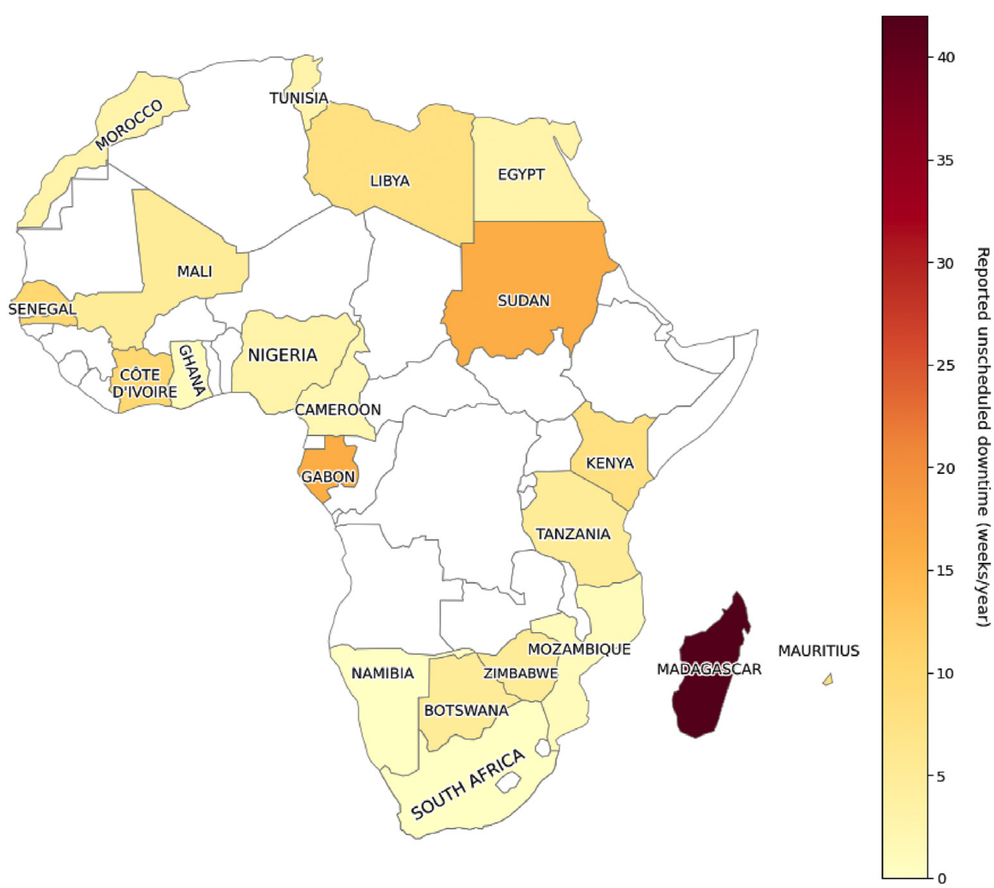

Fig 4. Reported unscheduled downtime for operational linear accelerator (LINAC)-based radiation therapy facilities in weeks/year.

the survey of facilities with LINAC-based radiation therapy across the 28 African countries shows unscheduled downtime levels from several weeks to 10s of weeks per year (see Figure 4). This most certainly identifies a direct and critical need to significantly improve the operational robustness of these and other LINAC-based radiation therapy clinical treatment facilities.

These results will be compared to the experience with LINACs in MICs and HICs. One limitation of the study is the fact that complete information on service contracts was not provided by all respondents because medical physicists did not always have access to all of the administrative information that was requested.

Further data acquisition to 'fill in gaps' in the desired data is ongoing and will be analysed in a subsequent report. The participating MIC and HIC radiation therapy facilities represent a variety of settings in terms of economic resource levels, healthcare infrastructure, public and private hospitals and different manufacturers and ages of the radiation therapy machines, which will provide insights on the differential influence of these variables on technology performance. Data from facilities in HICs can help to discern whether resources or environmental factors, or both, affect LINAC performance in LMICs. Interestingly, this study can address whether new technologies designed to improve the reliability of radiation therapy machine performance in LMICs can have potential benefit in HICs.

Conclusion

This study has provided an important snapshot of a dynamic healthcare situation in Africa as exemplified by Togo acquiring a dual-energy LINAC since we initiated our survey and that Ethiopia has acquired several LINACs, yet to be installed, to complement their one operational LINAC. Hopefully, this is the beginning of a wave of LINAC acquisitions in Africa. As additional data are obtained, we will be able to provide a detailed analysis of the factors most commonly associated with LINAC performance, especially downtime, in LMICs. This may provide information of interest to management and health policy officials in HICs and MICs, as well as to those in LMICs regarding the potential to mitigate some of the factors that affect LINAC downtime in the current environment in LMICs. The ongoing data analysis, an understanding of what aspects of the improvements are most critical and the implementation of solutions can contribute to improving the timely and effective treatment of patients with cancer, thereby reducing mortality as well as improving the palliation of symptoms caused by advanced cancers, a common problem in LMICs.

Clearly, a one-size-fits-all approach will not work in such diverse settings. It is important to note that new technology should be introduced in a contextual manner so as not to disrupt existing health systems inadvertently, especially with regards to existing staffing, infrastructure and socioeconomic issues. However, aggregating the detailed responses, opinions and suggestions from the teams of medical physicists and radiation oncologists that participated in this report forms the basis for the development, both from 'bottom-up' data and 'top-down' experience, of a set of critical solutions appropriate for each setting.

Critical for the success of this study was the establishment of a productive global collaboration among the scientific and medical communities, as previously shown by the ENLIGHT network [27,28], which includes healthcare representatives from MICs, HICs and LMICs. This study was uniquely represented by facilities -from all 28 African countries with LINAC-based radiation therapy. All participants are joined in the common purpose of improving access to LINAC-based radiation therapy in LMICs. The high level of engagement by individuals and participation of individuals in African facilities in this study was achieved primarily due to the trust developed among participants that was established during this multi-year collaboration.

This unique international interdisciplinary collaboration with and among clinical oncologists, radiographers, dosimetrists, medical physicists, engineers and other healthcare professionals involved in radiation therapy forms an invaluable asset, not only for the attainment of the goals of this study, but as a platform for subsequent informative surveys in Africa to evaluate the effects of improvements and innovations in cancer care that are implemented.

In summary, the ultimate aim of this study is to target radiation therapy technology developments to produce a robust LINAC that is capable of performing well in challenging environments, such as those encountered in many LMICs, and that will require fewer qualified experts for routine operation and maintenance, especially those personnel who are currently lacking in LMICs. The detailed analysis of the information from this study that will be reported later will complement general LINAC design considerations that include well-recognised factors such as ease of operation, reliability, robustness, easy repairability, self-diagnosis of subsystem faults, insensitivity to power interruptions, lower power requirement, reduced heat production and easy upgradability.

Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clon.2021.05.008.

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