50 years of radiotherapy research: Evolution, trends and lessons for the future

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\textbf{A R T I C L E  I N F O}

Article history:
Received 13 July 2021
Received in revised form 17 September 2021
Accepted 27 September 2021
Available online 4 October 2021

Keywords:
Evolution of radiotherapy
Inequity
Global
Trends
Radiotherapy access

\textbf{A B S T R A C T}

Rapid and relentless technological advances in an ever-more globalized world have shaped the field of radiation oncology in which we practise today. These developments have drastically modified the \textit{habitus}\textsuperscript{1} of health professionals and researchers at an individual and organisational level. In this article we present an analysis of trends in radiation oncology research over the last half a century. To do so, the data from >350,000 scientific publications pertaining to a yearly search of the PubMed database with the keywords \textit{cancer radiotherapy} was analysed. This analysis revealed that, over the years, radiotherapy research output has declined relative to alternative cancer therapies, representing 64% in 1970 it decreased to 31% in 2019. Also, the pace of research has significantly accelerated with, in the last 15 years, a doubling in the number of articles published by the 10% most productive researchers. Researchers are also facing stronger competition today with a proportion of first authors that will never get to publish as a last author increasing steadily from 58% in 1970 to 84% in 2000. Additionally, radiotherapy research output is extremely unequally distributed in the world, with Africa and South America contributing to ~3% of radiotherapy articles in 2019 while representing 23% of the world’s population. This disparity, reflecting economic situations and radiotherapy capabilities, has a knock-on effect for the provision of routine clinical treatment. Since research activity is inherent to delivery of high quality clinical care, this contributes to the global inequity of radiotherapy services. Learning from these trends is crucial for the future not only of radiation oncology research but also for effective and equitable cancer care.

Cancer is the second leading cause of death globally, causing an estimated 9.6 million deaths in 2018. Furthermore, it is considered a major worldwide public health issue because of the associated socio-economic impact [1]. Radiotherapy is one of the most effective treatments for cancer with more than half of all patients eligible for either palliative or curative treatment [2,3].

The field of radiation therapy has grown rapidly and has undergone profound changes since the early discoveries by W. Röntgen and M. Curie of X-Rays and Radium in the 1890s. Of particular note are the scientific breakthroughs in imaging, such as the development of Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), which have significantly enhanced the visualization of anatomy and through that have improved cancer diagnosis and treatment. In parallel, the invention of the linear accelerator, now the basis of modern external radiotherapy, and the expansion of radiobiological knowledge has greatly improved the treatment of malignant disease and the sparing of surrounding healthy organs.

Computing technology has also made a dramatic contribution in treatment planning and delivery.

Concurrent with these advances in radiotherapy over the last 50 years has been the transformation in tele-communications and in particular the internet. The revolution in connectivity has simplified the pooling of resources as well as the storage and access of scientific information.

This evolution has resulted in an acceleration of the pace of research particularly within countries with existing access to these resources, hence widening already large geographical disparities [4]. At the same time as the advent of the modern digitalised society, there has been a marked increase in pressure on academics to publish and for funders to ‘quantify’ the value of that research. These circumstances have fuelled the competition in research which, while stimulating the scientific community and promoting...
its excellence and ability to innovate, may also have negative consequences.

These rapid and relentless technological developments in an ever-more globalized world have shaped the field of radiation oncology in which we practise today.

To gain a deeper understanding of this evolution and the resulting trends in radiation oncology research we undertook a data-driven en-masse analysis of the last 50 years of literature in radiation oncology. In this article, we present the results of this analysis reviewing where we have come from and where we are now, with a pseudo-Socratic reflective approach, and provide insights and lessons for the future. By looking at the data in this unique way we show a dynamic picture of the shape of radiation oncology and its future direction of travel, which has wide-reaching implications for researchers, funders and future research priorities.

Materials and methods

The PubMed database was searched with the keywords cancer radiotherapy while restricting the date of publication in order to analyse the research output year by year from 1970 to 2019. This search yielded 358,114 publications distributed over the 50 years, as shown in Fig. 1 Panel A, and for which different characteristics were fetched and stored for subsequent analysis. In particular, the journals, the authors and their affiliations, the titles, the language used as well as the abstracts when present, were collected. The parsing of the PubMed database as well as the subsequent analysis of the data was performed using Matlab software (MathWorks Inc., MA). Please note that in this article, the words radiotherapy, radiation oncology and radiation therapy are used interchangeably.

Comparison to other fields

To understand the evolution of cancer therapies used in conjunction with, or in addition to, radiotherapy, the proportion of scientific publications returned with keywords pertaining to the following cancer therapies, in addition to cancer radiotherapy, was assessed: cancer immunotherapy, cancer chemotherapy (not radiotherapy), cancer hyperthermia, cancer hormone therapy, cancer stem cell therapy.

Publications & journals

Focusing on the results returned with the keywords cancer radiotherapy, the number of scientific articles as well as the number of journals were analysed year by year. The number of publications in the 20 journals with the biggest research output was plotted as a function of time (Fig. 2 Panel A).

In order to determine the journals that publish most of the impactful articles, the most cited 20%, 10% and 5% publications...
Fig. 2. Journals that contribute the most to radiotherapy research output, in absolute number of publications and highly cited articles. Panel A illustrates the cumulated contribution in publications of the 20 journals with major radiotherapy research output over the 50 years studied. Panel B, C and D show the relative contribution of journals that published, in at least one year, more than 3% of the most cited 20%, 10% and 5% of publications (i.e. most impactful articles).
were identified yearly and the relative contribution of the journals to this highly cited research output plotted, provided it was greater than 3% (Fig. 2 Panel B, C and D).

The language used in the publications was also collected and the proportion of English and non-English articles evaluated (Supplementary Material 1).

Cancer sites
To quantify the proportion of research output dealing with specific cancer sites, the publications were categorized depending on the presence of specific keywords (in Supplementary Material 2) in their titles. In this way, the yearly number of publications relating to cancers of specific anatomical regions was evaluated. Provided that the searched keywords were found, the articles were classified in one of the twelve following categories: gynaecological, gastro-intestinal, genito-urinary, haematologic, liver and biliary, skin, breast, ocular, lung, central nervous system, head and neck regions as well as sarcomas. The accuracy of the classification was assessed on a representative sample of 400 titles. The proportions of the cancer site-specific publications were compared with their corresponding cancer burden reported by GLOBOCAN for 2018 via the number of new cases and the number of deaths per cancer site.

Affiliations
The authors’ affiliations were analysed between 1990 and 2019 and the number of publications per city and country was determined. To visualize the geographical distribution of research output and its evolution, the number of articles per city was plotted on a map and displayed in a video format in Fig. 3. Also, the relative contribution of each continent to total research output was plotted as a function of time (Fig. 4). The analysis was restricted to this time interval in order to ensure that a significant proportion of articles had affiliations filled. This percentage was >88% in 1990 and increased steadily until 2019 to reach 99%.

To investigate relationships between economy and research output, the yearly number of publications per country was normalized per head of population [5] and plotted as a function of GDP per capita [6] in video format for the period studied (Supplementary Material 3).

In addition, to visualize how different countries balance their research output and radiotherapy capabilities, the normalized number of publications for 2019 was plotted as a function of the most recent total number of radiotherapy machines as reported in the Directory of Radiotherapy Centres (DIRAC) database [7] in Supplementary Material 4.

Themes
In order to visualize trends that took place in radiation oncology research, the number of articles which referred to specific themes such as technologies, fractionation or clinical practice was evaluated and plotted in Fig. 5. To do so, a list of keywords, detailed in Supplementary Material 5, was drawn up for each theme. The presence of one of these keywords in the articles’ title or abstract determined their theme classification.

Authors
Different metrics were calculated based on the authors’ names considering the twenty journals with major research output as displayed in Fig. 2 Panel A.

In an attempt to infer robust metrics for characterising the “publish or perish” culture facing radiation researchers, especially younger scientists entering the profession, we examined potential links between publication rates, career progression and how this has evolved over time. Within the scope of this analysis, we evaluated the total number of previous publications per last and first author every year between 1970 and 2019 as shown in Supplementary Material 6. In addition, we evaluated the number of publications before publishing as last-author. The number of years between the first publication and the first publication as a last author was calculated. The average number of authors per publication was also evaluated.

The pyramidal structure of research creates a competitive environment, which, while stimulating productivity, can also lead to negative outcomes such as poor mental health. PhD students and postdoctoral researchers are at the base of this academic system and are employed on temporary contracts for extended periods.
The loss of talent, skills and knowledge of those who do not go on to permanent academic positions is a wasted opportunity for both these highly skilled researchers and the community [8–14]. As a surrogate for this phenomenon, we therefore calculated the proportion of authors who have published as first authors, but never as last, and how this has changed over time.

**Results**

The distribution over the 50 years studied of the 358,114 publications returned in PubMed when searching the keywords cancer radiotherapy is illustrated in Fig. 1 Panel A. While in 1970 more than 53% of the articles were published in a language other than English, this proportion declined steadily to reach 4% in 2019 (supplementary Material 1). German, Russian, French and Japanese were the major non-English languages before a decrease in Russian articles was observed from 1992. From the year 2000, the proportion of articles written in Chinese progressively increased and Chinese became the major non-English language in 2019 representing 25% of the non-English research output.

As illustrated in Fig. 1 Panel B, the proportion of articles on radiotherapy, when compared to alternative cancer therapies used in conjunction/combination, was 64% in 1970 and decreased until 2019 to reach 31%. Conversely, chemotherapy was the topic of 4% of the articles in 1970, percentage which increased to 30% 50 years later. Since 2012 the proportion of articles on immunotherapy more than doubled passing from 9 to 19%.

The number of journals nearly doubled in the first 30 years of the analysis with an increase from 547 to 1078. The time necessary for the next doubling was then halved, with the number of journals reaching 2163 in 2014. The increase then slowed further, with 2244 journals as of 2019.

As detailed in Fig. 2 Panel B, C and D, in the 50 years studied, 17 journals published in one year more than 3% of the 20% most cited publications. For the 10% most cited articles this was 22 journals and for the most cited 5% 30 journals. The four journals that published the majority of the 20%, 10% and 5% most cited articles were found to be the same and are in descending order: International Journal of Oncology* Biology* Physics, Cancer, Journal of Clinical Oncology and Radiotherapy and Oncology. Their respective median [range] two year impact factors in the period 1999 to 2019 are: 5.0 [2.8–5.9], 5.9 [3.3–6.7], 15.6 [7.9–19.9] and 4.6 [2.5–6.2] [15].

As shown in Fig. 5, the percentage of publications referring to Computed Tomography started to increase rapidly from 1975 and reached nearly 18% in 2019, which makes it the most referenced keyword studied in radiotherapy research. It should be noted that CT initially related only to diagnostic imaging and later evolved to be incorporated into the radiotherapy planning pathway. More recently, it has taken on an additional role in image guidance,
Fig. 5. Evolution of the importance of different themes in radiotherapy research. This Figure shows the number of articles for which the titles or the abstracts contained specific keywords relating to technologies, fractionation or clinical practice. Each field or category plotted is associated with several keywords as listed in detail in Supplementary Material 5. Panel A and B show the number of articles referring to themes, here all pooled together, in absolute and relative numbers, respectively. Panel C, D, E, F, G and H focus on keywords belonging to specific categories: Delivery, Functional Imaging, Harmonisation of prescription reporting, Image-Guidance, Imaging and ‘other’, respectively.
Fig. 4 (continued)
through cone beam kV CT and fan beam MV CT, such that the term 'CT' has an expanded definition and role.

Research concerning the other major imaging breakthrough, Magnetic Resonance Imaging (MRI), started increasing in the early 1980s climbing to 6% of published articles in 2019. The term may increase partly as the result of the introduction of MRI linear accelerator machines, in a way analogous to CT, although the scale is rather lower. Chemotherapy and brachytherapy are also keywords with major long-term appearance as they were found to oscillate between nearly 4% and 6% in the period studied. Stereotactic radiotherapy is also amongst the most referred technologies amounting to nearly 7% of articles mentioned in 2019 but started appearing from the late 1980s.

As may have been expected, the use of Cobalt-60, which was the most commonly occurring keyword in 1970, with a mention in almost 3% of the publications, decreased progressively until it became insignificant in the mid-1990s. This corresponds to the first increase in the use of the words relating to linear accelerators (while remaining lower than 0.5%).

The terminology proposed by the International Commission on Radiation Units and Measurements in report 50 published in 1993 [16] for the purpose of harmonizing prescription, recording and reporting was gradually accepted by the community. 'Planning Target Volume' was the term most referred to as it was mentioned in 2% to 3% of the research articles from 15 years after the publication of the report.

Focussing on the last 20 years, the developments that were found to be on a significant rise are: Intensity Modulated Radiation Therapy (IMRT) from the end of the 1990s, Volumetric Modulated Arc radioTherapy (VMAT), stereotactic radiotherapy and proton therapy.

The proportion of publications dealing with specific cancer sites and pertaining to a search with the cancer radiotherapy keywords is shown in Fig. 6 Panel A. These figures reflect changing or stable practice involving radiotherapy over time. The accuracy of the categorization was found to be 91.5% and the proportion of identified sites gradually increased from 54% to 68% in the 50 years studied. The proportion of published articles dealing with hematologic malignancies was 11% in 1970 and dropped to 3% in 2019. Research output on gynaecologic malignancies followed the same trend, dropping from 17% to 6% in the same time interval. However, for lung, gastro-intestinal and central nervous system malignancies, the trend was the opposite with their respective proportions increasing from 6% to 11%, 8% to 16% and 6% to 15% in the 50 years.
analysed. Overall, no significant and sudden shift towards a specific site can be observed and the changes are gradual.

When comparing the proportion of research output per cancer site with the incidence and mortality data reported by the Global Cancer Observatory for 2018 [17] (Fig. 6 Panel B), central nervous system malignancies represented 14% of the 2018 research output with identifiable sites, while they are diagnosed in 3% of cancer patients and responsible for 2% of cancer deaths. Similarly, head and neck cancers were the subject of 17% of articles while their incidence and mortality were of 5% and 8% respectively. It is interesting to note a similarity between percentage of research output and mortality for several cancer sites: breast (11% versus 12%), gastro-intestinal (15% versus 19%), lung (13% versus 12%), liver/biliary (4% versus 6%), gynaecologic (6% versus 8%), genitourinary (12% versus 14%).

The number of authors (median [first-third quartiles]) per article increased from 2 [1–3] to 7 [4–10] between 1970 and 2019. The number of years (median [Q1-Q3]) between the first publication as a first author and the first publication as a last author remained relatively steady at 8 [4–14] between 1970 and 2000, with a 90th percentile around 20 years preventing parts of our analysis on the last twenty years.

The proportion of first authors that did not publish an article as a last author was 58% in 1970 and increased steadily to reach 84% in 2000. The mean total number of publications before the first publication as a last author remained relatively steady at 8 [4–14] between 1970 and 2000, with a 90th percentile around 20 years. In 2019 this number increased to 5 [2–13–34] and 16 [5–38–82] for first and last authors, respectively.

Cities were identified in 88–92% of affiliations’ lines in the period studied. The geographical distribution of research output is illustrated in Fig. 3. In this figure, the number of publications from cities found in the affiliations were displayed on a map as a function of time in a video format with a focus on Asia, Europe, North America as well as with a global world view. The huge differences, especially the relatively low research output from Africa, is striking. As illustrated in Fig. 4 Panel A, Africa represented between 0.5% and 1% of the total research output during the 50 years studied with a slight increase in the last decade. In 1970, 12% of the articles were published in a country located in Asia. This proportion more than doubled in 50 years and reached 26% in 2019. Europe contributed to 47% of research output in 1970 which despite remaining relatively stable, decreased slightly to 42% in 2019. The proportion of articles published in North America dropped from 38% in 1970 to 26% in 2019. In 1970, 1.7% of the research output was published in a country located in the Oceania region. This percentage rose to 3.3% in 2019. While remaining below 2%, the number of publications from South America followed a clear trend towards increase. When the research output was normalised by head of population, (Fig. 4 Panel B), Oceania is the most productive region in the last decade, followed by North America, then Europe and finally Asia.

Fig. 6. Evolution over the past 50 years of the proportion of research output dealing with specific cancer sites. Panel A shows the evolution of the proportion of radiotherapy research output dealing with cancer sites as detailed in the legend. Panel B allows for comparing the proportions of research output for 2018 with the number of cancer cases and deaths reported by the Global Cancer Observatory (Globocan) in the same year for all the sites studied.

2 Oceania: a geographic region that includes Australasia, Melanesia, Micronesia and Polynesia.
Discussion

This study presents a panoramic view of the evolution of radiotherapy research over the last 50 years. Via the analysis of the trends that took place in the field, this study sheds new light on both technological and human aspects of the developments. The impact of technological advancements providing step changes in research topics is clear. This analysis also provides evidence of the impact of geo-politics, for instance the decrease in articles written in Russian following the collapse of the Soviet Union or the rise in research output from South East Asia reflecting rapid economic growth. The lack of research from Africa is striking and mirrors the lack of financial resource and inequity in cancer care.

It is important to note that this analysis focuses on research output of radiation therapy and relies on the PubMed database and search engine and is therefore not wholly representative of the field of radiation oncology. Some of the metrics developed for the purpose of this study are surrogates of phenomena and while they may not perfectly represent the reality, they have the virtue of describing trends. In particular, the number of first authors that will not become last authors is based on the 20 major journals (listed in Fig. 2 Panel A). Whilst this may not perfectly capture the complexity of the discipline, it can be considered a representative sample.

Valuation of research

The journals that published the major proportion of the most cited papers have relatively low impact factors despite being among the leading contributors to the field. Indeed, three of the four journals that publish much of the most cited basic scientific and translational research in the field have impact factors around 5. The fourth has a higher impact factor of 15, which may be due to the high proportion of randomised phase 3 clinical trial results published in this journal. We suggest two key reasons for this result. The first is that, as shown in Fig. 2, these journals publish a large number of articles, some of which necessarily end up with lower numbers of citations, thus counterbalancing the journals' impact factor. The second is that radiation oncology is a small and self-contained field relative to others in cancer research and medicine. Thus, even the best work in the field often has no real relevance to researchers in other areas, and it is therefore inevitable that total citation numbers will be lower. In addition, clinical trial results, typically from randomised trials, are regarded more highly than the technology developments which are necessarily required for those trials to be performed. This analysis highlights the limitations of the impact factor as a means to evaluate the quality of a journal, its importance for the field and of the publications it contains. The present results also question the relevance of this metric for comparing research quality between fields which is common practice for funding bodies who often turn to this criterion to rank researchers and allocate grants.

Transformative innovations

Radiotherapy is an innovation- and technology-driven specialty that has rapidly evolved over the last 50 years. The semantic analysis of the titles and abstracts quantified the utilization of specific technologies and practices by the field of radiation oncology. Some technological developments such as CT and MRI have had a major influence on the direction taken by the field, with 18% of publications referring to CT technology in 2019. Furthermore, the present study shows that it took 15 years for the community to gradually accept the terminology proposed by the ICRU in 1993 for the purpose of harmonizing prescription, recording and reporting and the proportion of use of these terms remained stable since then.

Cancer sites

Some discrepancies were noted between the burden of site-specific cancers reported by GLOBOCAN [17] and the focus of radiation oncology research. In particular, malignancies in the head and neck or involving the central nervous system were over-represented in research compared to their burden. The fact that research done does not match the incidence of the disease may reflect the implementation of new technologies for specific sites, such as the use of protons or carbon ions for treating the aforementioned malignancies. It may also reflect the ease with which clinical studies can be performed, especially considering outcome endpoints which can be seen within a short timeframe. For several other cancer sites including, breast, gastro-intestinal, lung, liver/biliary, gynaecologic and genito-urinary malignancies, however, research output and mortality proportions were found to be similar. These results do not contain data on research spending. A simple comparison of research output with incidence and deaths is an important step although more sophisticated analysis methods are available to represent societal and individual disease burden [18] and should be considered in future analyses.

Radiotherapy and alternatives

The overall proportion of publications dealing with cancer in PubMed has increased from 6% in the 1950s to 16% in 2016 [19]. However, our study has found that the proportion of these articles which deal with radiotherapy, compared to other cancer therapies, has declined from 64% to 31% in the last 50 years. This number, likely partly reflecting the prioritisation in budgets allocated to research, is to put into perspective considering more than 50% of cancer patients are eligible to benefit from a radiotherapy treatment [23]. The decisions made by funding bodies are pivotal in defining the direction taken by our field. While both academia and the industry play important roles in research developments, and partnerships between the two are crucial to successfully translate innovations into the market [20], the domination of the sector by private companies could drive research towards a direction that eventually serves financial interests as opposed to common good. In recent decades, pharmaceutical companies dominated cancer drug development which translated into profits and shareholder value becoming predominant considerations in decision making [21]. The greater profitability of oncologic drugs [22] compared to other sectors, could explain in part why chemotherapy research output, aided by the financial support of pharmaceutical companies, was multiplied by 7 in 50 years. Despite the dramatic growth in research in this field, we are yet to see the gains in cure that were predicted by President Richard Nixon in 1971 when signing the National Cancer Act [23,24].

Human aspects of research

The soaring number of publications on cancer in recent decades can be partially explained by the rise in funding sources [25] and is of much larger magnitude than the increase in incidence of the disease [19] despite an increase of 47% in new cancer cases between 2020 and 2040, as estimated by GLOBOCAN 2020. Another reason for this rise, is the apparent increased productivity of researchers. The number of articles published by the 10% most productive last authors more than doubled in the past 15 years. This augmentation can be seen as the result of different factors including telecommunications developments as well as stronger competition. In the past 35 years, the world has been conquered and connected by the
internet and the growth in internet users resembles that of research output observed in this study (Fig. 1 Panel A).

The strengthening of competition in research is illustrated by the increase of the proportion of research contributors to temporary contracts who will never have senior positions. In the present study, the proportion of first authors that will never publish articles as a last author was found to have increased from 58% to 84% between 1970 and 2000, which is a worrying trend. A previous study on biomedical research in the US reported that since 1982 the number of grant-eligible basic-science faculty [principal investigators] younger than 46 dropped, while in the same period funds for the National Institutes of Health (NIH) almost tripled. In addition, the fraction of basic-science principal investigators successful in their grant applications dropped for those younger than 46 and increased PIs older than 55. The authors estimated that this age biasing of the research milieu could jeopardise future biomedical research [26]. These data suggest that an increasing proportion of a growing budget of research funds is being allocated to a reducing number of senior academics [27]. At the same time the enhanced competition and job insecurity this confers may be impacting the mental health of researchers, with between half to two thirds of postdoctoral researchers perceiving their professional prospects as difficult [28,29]. More worrying, less than 50% of the postdoctoral researchers 'would recommend a scientific career to their younger self’ [30]. Additionally, the recent implementation of austerity policies in a number of nations was shown to have negatively impacted the mental health of researchers [31,32].

The median number of authors per publication rose from two to seven in the past 50 years with the third quartile increasing by seven, from three to ten. This increase can be partly explained by the expansion of scientific knowledge which promotes specialisation of scientists [33] on both technical and clinical aspects. Moreover, research projects have become more ambitious and complex and nowadays result from multidisciplinary teams, necessitating the expertise of researchers from various fields. In addition, the rising number of collaborations between centres also tips the scales in favour of large authors’ lists. Another explanatory factor may be the consideration of authorship as a means to assign credit and subsequent career benefits, which may drive researchers to include more co-authors and could result in aberrations (e.g. ghost- and gift-authorship) [34]. Making credit prevail over responsibility and accountability may result in artificially growing scientific output with the risk of internal inconsistency. In addition, the increased specialisation can decrease the ability of scientists to critically evaluate work outside their domain of expertise. This phenomenon makes it harder for co-authors to take accountability in published works. The use of tables detailing credit and responsibility among co-authors may be a way forward [35]. Another negative consequence of the hyper-specialization of scientists is the difficulty to evaluate the work of others which is at the core of the oversight of research via the peer-review process.

A separate aspect of hyper-specialisation is the difficulty in developing cross-disciplinary work which requires funding disbursed through a peer-review process. Where ‘silos’ are too restrictive, peer-reviewers may not be able to capture the full value of proposals. In turn, this may disadvantage researchers working within a restrictive funding environment.

Geographical disparities

Radiotherapy research output is very unequally distributed in the world. Africa and South America represented 23% of the world’s population in 2019 but contributed to around 3% of radiotherapy articles, while North America and Europe contributed to two thirds of research output despite being home to less than 15% of the world’s population. The contrasts observed in Fig. 3 match remarkably the geographical representation of the number of funders identified in a previous study [25]. Some initiatives have started to work towards correcting these marked geographical discrepancies, as illustrated in Fig. 3 [36–40]. Since research activity has a knock-on effect on the delivery of clinical radiotherapy (and other) services, this is a major challenge in providing equity of access to cancer care.

These differences reflect the underlying disparities in the access to radiotherapy treatments. In 54 nations composing Africa, as of May 2021, 24 countries did not have a single external beam radiotherapy machine and 34 did not have brachytherapy resources [7]. In low and middle income countries 31% of teletherapy machines use Cobalt-60 [41]. Additionally, it was reported that in low income countries, only 10% of the population had access to radiotherapy treatment [41–43]. It is estimated that the number of external beam radiotherapy machines needed in low and middle income countries corresponds to about twice the radiotherapy equipment of Europe [41].

Research, by promoting the expansion of knowledge and of technological developments, is an essential means to improve cancer outcomes. Moreover, the transposition of treatment protocols implemented in developed countries to low/middle income nations may yield suboptimal results given the marked differences in human and physical resource availability [44]. As innovation remains crucial for the development of radiotherapy technologies which are robust in economically poor environments, there is a critical need for low/middle income countries to be facilitated to undertake further radiotherapy research [45]. Humanity would benefit from having more evenly distributed, affordable and equitable radiotherapy cancer care not only through the saved lives attributable to cured cancer cases but also from the associated positive economic benefits [45].

Conclusions

In the last half century, the collaborative efforts of researchers, bolstered by technological developments, have resulted in tremendous progress in the ways we treat patients with cancer. By analysing the data of more than 350,000 scientific publications, the present study sheds light on the evolution of different aspects at the core of radiation oncology research. This analysis has revealed that, over the years, radiotherapy research output has declined relative to alternative cancer therapies, likely as a result of the changing priorities of funding bodies. In addition, the pace of research has significantly accelerated with, in the past 15 years, a doubling of the number of publications from the most productive last authors. Researchers are also facing stronger competition today with an increasing proportion of first authors that will never get to publish as a last author. Additionally, radiotherapy research output is extremely unequally distributed in the world, with Africa and South America contributing to around 3% of radiotherapy articles in 2019 while representing 23% of the world’s population. This disparity, reflecting economic situations and radiotherapy capabilities, has a knock-on effect for the provision of routine clinical treatment.

Despite the overall significant progress in technological developments and publication output made in recent years, our study highlights that some aspects are stagnating or worsening. Our findings call for additional interventions to address the drivers of disparities in radiotherapy, a review of funding mechanisms, and proper valuation of research and researchers. Learning from these trends is crucial for the future not only of radiation oncology research but also of effective, equitable cancer care.
Competing interests
The authors declare no competing interests.

Data statement
The data analysed in this study is publicly available online at the following URL: https://pubmed.ncbi.nlm.nih.gov/.

Acknowledgements
This work was generously supported by contributions from 1) The Chief Scientist Office Scotland IMAGE-IN grant (TCS/17/26 - CSO Award) and 2) the NHS Lothian Edinburgh and Lothians Health Foundation (charity number SC007342) Jamie King Uro-Oncology Endowment Fund.

Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.radonc.2021.09.026.

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