



Original paper

A review of 3D printing utilisation in radiotherapy in the United Kingdom and Republic of Ireland

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ABSTRACT

The use of three-dimensional (3D) printing in medical applications is quickly becoming mainstream. There have been an increasing number of publications discussing its implementation in radiotherapy, and the technology has become more affordable.

The objective of this study was to establish how widely 3D printing is currently being utilised and what has been done to validate the processes and outcomes. A survey was sent to the UK and Ireland medical physics mailing lists. The questions were designed to establish how many centres were using 3D printers, how 3D printers were being utilized, the type of printing technologies being used, and how risk was being addressed.

A total of 60 radiotherapy centres responded to the survey, with 38 % of the respondents currently using 3D printing. The majority (85 %) of the remaining respondents said they may or would have a 3D printer in the next 3 years. The majority of users were using FDM-type printers. The main variability among 3D printer users was how risk management and QA were addressed.

This survey has demonstrated that there is an increased appetite for 3D printers in radiotherapy even beyond phantoms and bolus. Yet, despite this, guidance on implementation, compliance with the medical device directive and risk management remains sparse. As a consequence, centres have adopted a variety of approaches to risk management and QA.

1. Introduction

The process of three-dimensional (3D) printing is an additive manufacturing technique which takes a 3D digital object and creates a 3D physical object. In recent years there has been an increase in the utilisation of 3D printing from a niche speciality to a widely available technology with uses in a range of industries including healthcare. Its expansion into healthcare has seen uses including regenerative medicine, implants, dentistry, cardiology and orthopaedics [1].

The prints are often derived from a process involving several different software packages, where an object or organ is segmented or designed and this outline will then be converted to a code which will be used to drive the 3D printer. There can be 100 s of parameters or settings for 3D printing a single object resulting in a complex process. Several

parameters can be varied, such as infill and extrusion factors, each of which can affect the print density and also geometric dimensions [2].

Research in 3D printing is increasing but the landscape of utilisation in the clinics has yet to be quantified. A review on the analytics website has shown that there has been a 25-fold increase in publications where “3D printing” AND “radiotherapy” has been searched, 98 publications in 2014 compared to 1512 in 2022. This increase can be seen in Fig. 1 and matches the trends seen by recent reviews by Rooney et al. [2] and Tino et al. [3]. In 2019 Rooney et al. [2] undertook a systematic review of the 3D printing literature. At that time, the majority of publications involving 3D printing in radiotherapy involved phantoms (26 %), followed by brachytherapy applicators (20 %) and then bolus (17 %).

Tino et al. [3] concluded that Additive Manufacturing has great potential to improve the current practice of using different types of

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phantoms, due to low-cost material and extremely adaptive fabrication abilities of complex geometries, emulating patient conditions. They made similar conclusions that the majority of 3D printer users in radiotherapy were for printing phantoms with the majority for imaging purposes.

Several articles have discussed various advantages and challenges associated with the use of 3D printing bolus in radiotherapy [5–8]. The main advantage of 3D printing is the ability to produce custom-made bolus with improved conformality and time efficiencies. Some challenges that come with additive manufacturing of bolus include print fails, effective materials classification and ensuring uniformity of the bolus across the print. The employment of bolus in radiotherapy has been encouraged by the introduction of CE/FDA-marked software for the conversion of DICOM files to STL files specifically for the creation of bolus [9] and brachytherapy applicators [10]. One of the common approaches to this implementation can be seen in Fig. 2.

There has been much exploration into the use of 3D printing in brachytherapy. The main use is for surface-based brachytherapy, where the applicator is printed and then applied directly to the surface of the patient [11]. This has resulted in better skin conformality in areas with large contour variation [12]. In the radiotherapy realm, other uses that have been discussed include immobilisation devices [4,13–15], brachytherapy templates for seed delivery [16], and the design of oral stents for radiotherapy [17].

Despite the wide-ranging uses and the implications of legal regulations on custom medical devices, there are no consensus documents on how to implement 3D printing in the clinical radiotherapy environment. While much of the literature offers an interesting insight into how 3D printing is being integrated into individual departments, they do not provide an overview of how widely the technology is being utilised

across the radiotherapy community. This makes it challenging to establish the barriers to implementation. Indeed, Rooney et al. [1] reported that most published studies were preclinical feasibility studies (63%), with few clinical investigations such as case reports or series (13%) or cohort studies (11%) (see Fig. 3.).

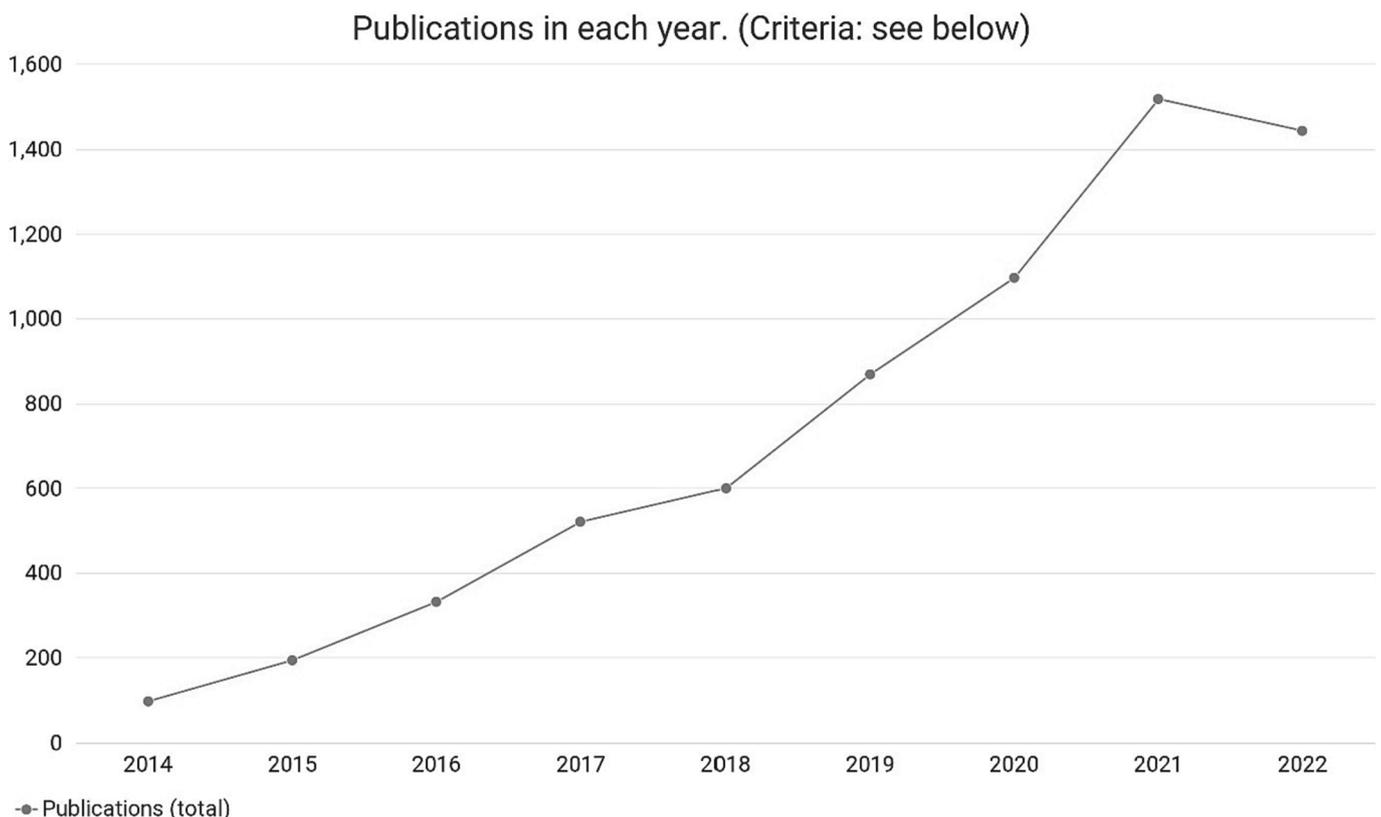
Previous guidelines reported in the literature have detailed the importance of QA procedures for both the printer and the resultant print [18]. While past QA recommendations focus on the consistency or accuracy of the 3D print quality, for radiological use, the material properties of the print must also be considered. It has been recommended that extensive imaging and dosimetric assessments must be performed on printing material considering tissue equivalence, as well as the impact of inter- and intra-print variations on outcomes [19], although these specifications can depend on the application [20].

In this paper, we sought to capture how 3D printing is currently being utilised across the UK and Ireland and establish the pitfalls that are preventing the further utilisation of this technology.

2. Materials and methods

A survey was developed to examine a range of metrics associated with the use of 3D printing in radiotherapy. Depending on the respondent's initial answers, the survey ranged between 3 questions for those not using 3D printing to 39 questions in cases where the printer was being used for multiple applications. The questionnaire was generated with Google Forms and designed to accept a single response from each radiotherapy centre.

The first metric examined was how widely 3D printing was currently being used in radiotherapy. For this metric, the authors asked how many centres were currently doing 3D printing in their centre. For those that



Source: <https://app.dimensions.ai>
Exported: April 05, 2023
Criteria: "3D printing" AND "Radiotherapy" in full data.

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Fig. 1. Publications through the years searched using keywords "3D printing" AND "Radiotherapy" using the Dimensions AI. 2014–2022 [4].

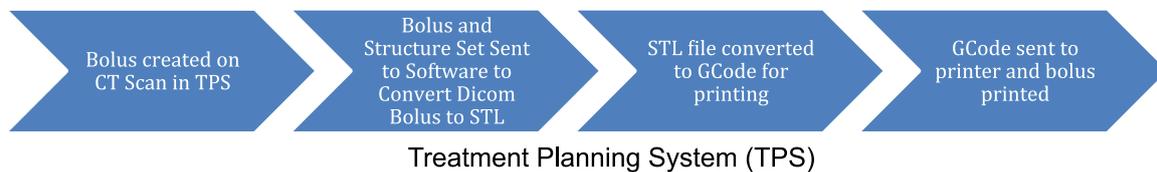


Fig. 2. A common workflow for creating 3D bolus in radiotherapy from the CT scan.

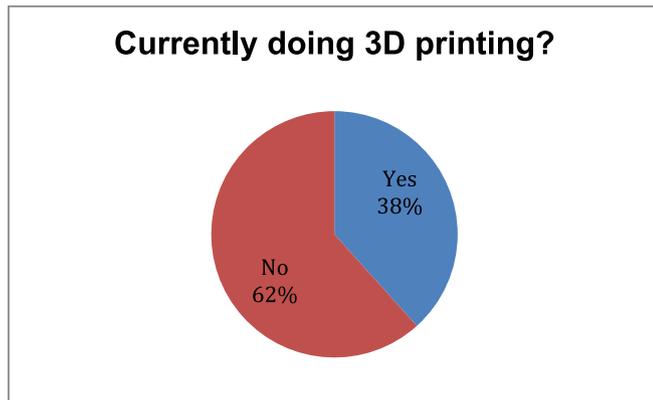


Fig. 3. Percentage of respondents currently using 3D printing.

currently weren't 3D printing, they were asked how likely they were to implement the technology in the next 3 years. For those that were 3D printing, there was also a question about whether out-of-house 3D printing was ever utilised.

The second metric examined was used to establish the type of 3D-printed objects that were being printed. The literature indicated that the main uses within radiotherapy were phantoms and bolus. As discussed in the introduction, some publications showed other uses outside of these. In this metric, we asked how people were using the printers. For bolus, there was a question about the sites being treated with 3D printed bolus. There were open questions asked about the type of phantoms being developed and how they were being used. In the final section for this metric, the respondents had the opportunity to discuss any other uses in radiotherapy.

The third metric looked at the types of 3D printing technologies being utilised. This established the types of printers that were being used (e.g. polyjet, FDM etc). In this metric, the materials being used were also examined. The fourth metric established what type of software is being used with 3D printing. This information was used to establish how widely freeware was being used and for what uses. The final two metrics were related, looking at risk assessments and quality management. The respondents were asked about what type of risk assessments they had in place. They were also asked about QA and post-print verification. This is summarised in Table 1. The aim was to assess how people were utilising 3D printing, with particular emphasis on the type of QA and risk management in place. Responses to the survey were received from 22/11/2021 to 27/01/2022. The key metrics are shown in Table 1.

3. Results

There were 61 Irish and UK centre respondents. All 3 out of 3 public centres in the Republic of Ireland responded and 55 of the 62 UK NHS (public) centres responded. The remaining 3 responses were either from private centres or unidentifiable centres. A duplicate response was removed from the data. For the 60 remaining responses, 38 % (23) were currently 3D printing. When the remaining were asked if they saw their centre utilising 3D printing in the next 3 years, 35 % responded yes, and

Table 1

Metrics being examined in the survey.

Metric	Details
<i>How widely 3D printing was utilised</i>	For this question, we asked how many people were currently using or considering using 3D printing.
<i>What is 3D printing being used for in radiotherapy</i>	This was broken down into 3 sections. Bolus (and moulds), phantoms and other uses. Participants had the opportunity to select multiple uses.
<i>What type of technologies were being used</i>	This included types of printers and materials being utilised. To establish the type of printers, we used an open-ended question to ask which printer people were using and then used that information to establish if they were FDM, Polyjet, SLA etc.
<i>Software type</i>	This was broken down into freeware and paid software, with a particular interest in the case of software with CE marking and its use in the manufacturing of medical devices. The use of DICOM data for phantoms was also explored.
<i>How risks and risk assessments have been addressed</i>	Two main questions were asked about risk. The first was about compliance with the HSC RRI146 guidelines for fumes. The second question was a generic question about risk assessments.
<i>What type of QA and verification is being performed</i>	These questions were designed to see if there was any variation across the departments in terms of QA and validation.

51 % stated they may consider the implementation of additive manufacturing. All respondents that 3D printed were using in-house printing as opposed to contracting an external provider to undertake the 3D printing on the Radiotherapy Department's behalf.

As can be seen in Fig. 4, the most popular use of the printer was for phantoms, the majority of departments use 3D printing for phantoms or similar proportions for phantoms and bolus, but almost a ¼ for other uses too. There were 5 centres that stated that they were only using 3D printing for other uses. This included spare parts for physics measurement equipment, Covid related PPE devices, brachytherapy applicators and immobilisation devices. In total 17 centres said they used 3D printing for uses other than bolus or phantoms. This was broken down into 7 categories and the breakdown is shown in Fig. 5.

Participants were asked to include the name and brand of the printer

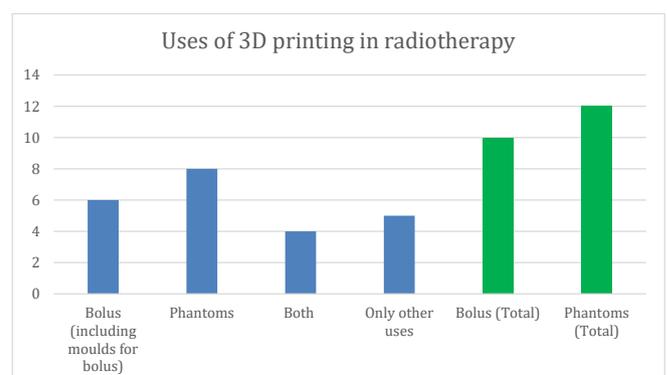


Fig. 4. 3D printing application in the radiotherapy department.

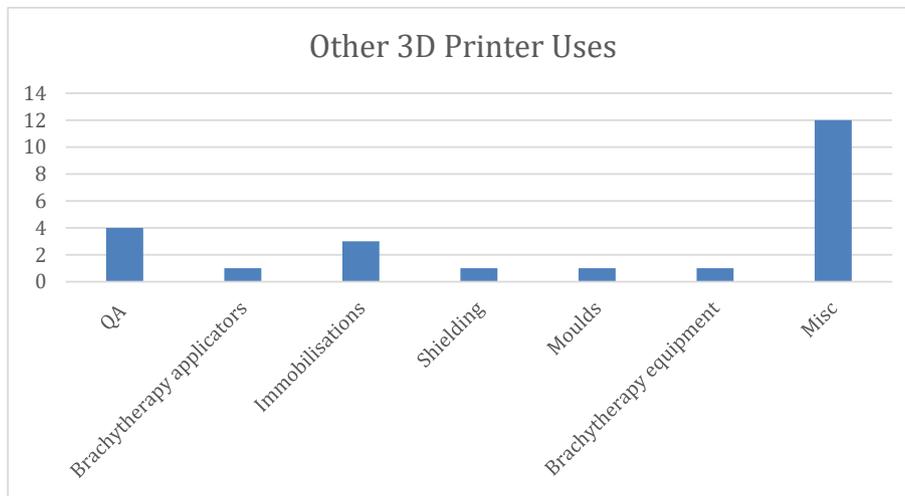


Fig. 5. Other 3D printer uses in radiotherapy.

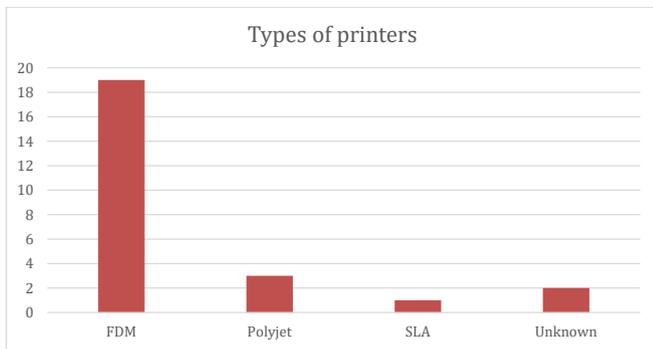


Fig. 6. The types of printers being utilised in departments.

in use at their centre. This information was used to establish which type of printer was used. Fig. 6 shows 83 % of centres were using FDM-based printers. Polyjet printers accounted for 13 % and 4 % had an SLA printer. The authors were unable to identify the type of printer from the response for 2 centres. There was one case where the printer was not owned by the hospital but by a private individual within the department. In this case,

the primary use was phantoms, not bolus. A total of three centres had access to more than one type of printer.

PLA was used as the primary filament type. The breakdown of materials used for bolus and phantoms is seen in Fig. 7. While there are no strict definitions between desktop and industrial printers there are some parameters that can be used to assess how advanced they are. Enclosed printers made up 74 % of the identified printers. There was a total of 25 printers in the hospitals and the authors had enough information to establish the print volume of 20 of them. This is summarised in Table 2. They are broken down by size where 8000 cm³ is equivalent to 20x20x20cm, 27000 cm³ is equivalent to 30x30x30cm, 42875 cm³ is equivalent to 35x35x35 and 64000 cm³ is equivalent to 40x40x40cm. In

Table 2
Printer sizes.

Build volume	Number of printers
0–8000 cm ³	2
8000–26999 cm ³	9
27000–42874 cm ³	0
42875–63999 cm ³	7
>64000 cm ³	2

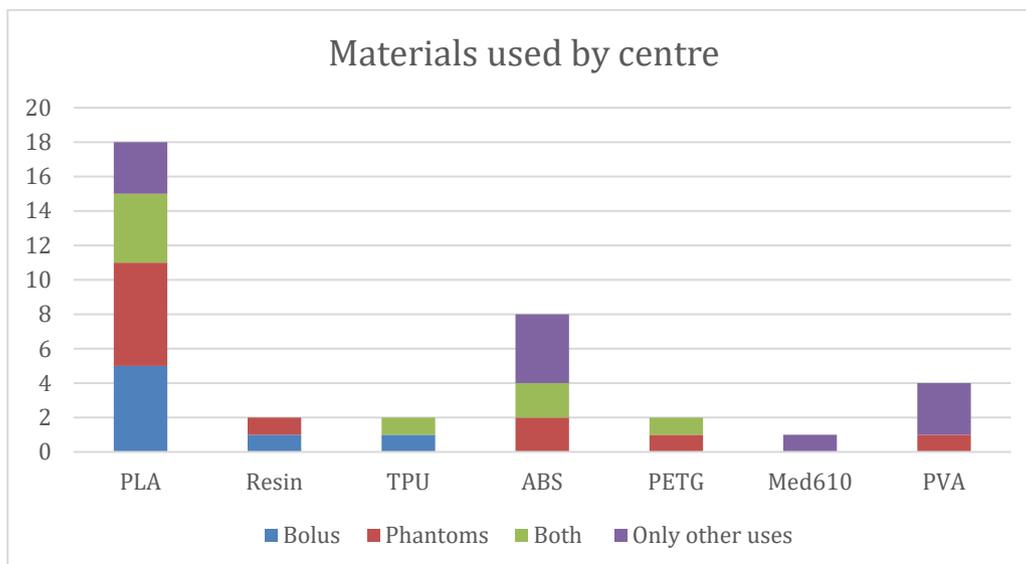


Fig. 7. Materials used for phantoms and bolus production.

Table 3

3D printed bolus in radiotherapy, areas of treatment and software used. Note the total number of respondents for this was 10, however, some centres did multiple sites.

Area of treatment	N	Software for creating STL
Head & Neck	8	3D bolus/Adaptiiv, Materialise Mimics, Slicer
Breast	1	3D bolus/Adaptiiv
Pelvis	2	3D bolus/Adaptiiv
Groin	1	3D bolus/Adaptiiv
Limb	2	3D bolus/Adaptiiv
Skin	1	3D bolus/Adaptiiv
Unspecified	2	3D bolus/Adaptiiv, Slicer

FDM printers where the exact model could be identified, 77 % had heated beds. It's possible that the remaining had heated beds retrofitted (see Table 3).

Almost all centres (except 2) also utilised the printer for other uses beyond phantoms or bolus. This included applications outside of radiotherapy, such as prototype surgical tooling, uses in maxillofacial and manufacture of spare parts across the hospital. Within radiotherapy, uses included replacement parts for QA devices, masks, shielding for electrons and patient support devices. In one case, the centre had used the printer for HDR applicators.

Looking at the 10 centres that were producing bolus, 60 % used commercial software CE marked to convert bolus into an STL format. The main software packages used in the creation of bolus and the sites treated are shown in Table 4.

A total of 58 % (7) of the participants making phantoms extracted data from medical images to produce phantoms. There was a variety of responses about what types of phantoms were being printed. These are listed in Table 4. There were 4 respondents that printed for general machine QC accessories such as jigs, 6 were anatomical phantoms such as head and neck or pelvis, 3 were for IGRT or motion management and 2 stated brachytherapy uses.

The majority (19) of the 23 centres performed overnight printing. Fume management as specified in the HSC RR1146 document [21] was done in 9 centres. Only 14 out of 23 respondents had performed at risk assessment on some part of the 3D printing process. The risk assessments that were included were:

- General risk assessments (Nothing further specified)
- Structural rigidity, accuracy and water equivalency
- Clinical use
- Overnight printing
- Risk to staff

Table 4

Types of phantoms and their uses.

What kind of phantoms are made	What are they used for
Head any others that are required	Research
LINAC Couch Isocentre phantom	Measuring couch isocentre accuracy
A few. One for gynae brachy. Pseudo anthropomorphic, one for holding farmer chamber for in air RT measurements	
Dosimetry Test objects	Routine IGRT QC
Currently creating adaptable pelvis phantom as part of research project	Adaptive radiotherapy QC / research project
Full size heads	Diagnostic projects.
Imaging phantom	Isocentre check
Cardiac	thoracic/cardiac verification
Imaging, research, IGRT, brachytherapy	Imaging studies on MRI, CT. Research in brachytherapy, Radiomics, imaging, IGRT
Prototype - testing	testing
Respiratory motion phantom, anatomical phantoms (skin)	Commissioning 4D CBCT, assessing patient dose
Laser jigs other	Mechanical measurements

- Risk to service if printer fails
- Infection
- Electrical safety

There was variety in terms of the type of risk assessments performed. For example, only 4 of the 14 departments that specified that they did a risk assessment, mentioned patient, clinical safety or dosimetry. All of these were centres using bolus.

There were 8 of the 23 centres that had a QA procedure in place, with 6 of the 10 centres producing radiotherapy bolus having a QA procedure with the remaining 2 centres using the printer for other uses. Centres only printing phantoms had no QA procedures in place. However, 19 of the 23 centres said that they took some steps to verify print accuracy. All 10 centres that created 3D printed bolus were performing some kind of print verification. For example, of the 19 centres that said they verified print accuracy, 10 mentioned CT, CBCT or scanning. Other methods of verification included physical measurements of the bolus and a monthly benchmarking print. The responses to the QA procedures can be seen in Table 5.

4. Discussion

This study has demonstrated that 3D printing is emerging as a key tool in the radiotherapy community, but that there are barriers to implementation on a wider level., Responses showed that a lack of guidance on how to get started, initial cost setup and a lack of clarity over medical device legislation could be issues. It is clear from the data that Quality Assurance Programs vary from centre to centre. There was variation in use of risk assessments, application of fume guidance measures and print specific QA.

Rooney et al. [2], undertook an extensive review of the literature and made the point in the conclusion that a lot of the literature was reflective of small cohort and clinical studies. This study has shown that the application in the clinical environment is growing. The Rooney review showed that the highest number of publications were phantoms, which matched the clinical utilisation shown here. However, our survey has also shown an appetite for 3D printed clinical bolus in the clinic.

Since this survey was conducted a similar study was published from Australia and New Zealand by Albantow & Brown [22] and some comparisons can be made. In their study they established a 23 % printer ownership compared with our studies 38 % of centres. However, in our study no centre outsourced 3D printing, while in their study 30 % of

Table 5

Printer QC procedures in place.

QC Procedure Described	Type of printing
PRINTER QC: Printing of 3D cube of known dimensions, using calipers to measure in three dimensions and record in spreadsheet. TPS PATHWAY QC: Printing of 10 cm × 10 cm × 1 cm model within Pinnacle, exporting it similar to any bolus we would print, and verifying measurements in a similar way.	Bolus
Plans to have monthly QA device printed	Bolus
Brachy test prints for dimensional accuracy and overall print quality. Temperatures, belt tensions, nozzle conditions verified.	Bolus
CT scan 3D print to ensure homogeneous and that there are no print issues not visible on the outside of the print. This also allows us to verify density changes over time. The printer also undergoes regular routine preventative maintenance which includes assessing print quality.	Both Bolus and Phantoms
We measure the job against a drawing	Both Bolus and Phantoms
Visual check with additional CBCT if required, CBCT on fraction 1 of patient treatment	Both Bolus and Phantoms
Management of Materials and Design for non-CE devices and innovation device modelling	Only other uses
Project verification and validation to ensure spec has been met.	Only other uses

centres outsourced 3D printing. This outsourced printing is also used in medicine in the US [23]. The introduction of on-demand 3D printing services within the UK and Ireland could help hesitant departments implement the technology without the need for the same level of risk management systems or dedicated staffing requirements. PLA remained the most common material used in both surveys. In the Australian and New Zealand study, bolus was the most common use, unlike our study where phantoms were the most popular.

The number of responses indicates that there is an increasing interest in the subject of 3D printing in radiotherapy. While there was a large variation in the printer make and model, the type of printer primarily used was FDM. FDM printing, which uses a hot extruder to melt material and lay it on a bed in the shape of the model, is often considered an entry-level printing technique [24]. These printers can print larger objects at a lower cost than other printers, so it makes sense that these are often used as the first printer type. The low cost and large build size make them ideal for phantoms. The two other types mentioned (polyjet and SLA) have the capability of producing higher resolution smoother finishes than FDM and use a different technique for production.

There was a variety of materials used for 3D printing. For phantoms, and most of the other uses, biocompatibility wasn't a question. For surface-based applications, the biocompatibility of the materials are relatively easy to establish and this should be specified on the data sheet provided for the material. Decontamination instructions and instructions around single patient use are readily available to prevent infection control concerns. However, as use moves to inter-cavitary and interstitial applications, this will need to be looked at more thoroughly. The two main materials used, PLA and ABS, have different density ranges. The exact densities will change from supplier to supplier, but, in general PLA is higher in density than ABS, which is close to water. In future work a study on how departments control density variations could provide valuable insight for implementation of 3D printing.

PLA, the most popular used material for both bolus and phantoms, has a specified 1.210–1.430 g/cm³. This has a higher density than typical bolus material. However, by varying the infill it would be possible to get an effective density similar to that of water. The second most popular material, ABS, has a physical density of 1.060–1.080 g/cm³ which is more equivalent to water. The physical density can be adjusted by changing the material infill [14,15]. It can be seen that head and neck dominates the 3D printed bolus. This is most likely due to head and neck bolus being generally smaller, but with complex shapes, which lends itself to a 3D printed solution.

Phantoms were the main application of 3D printers in radiotherapy. Phantoms in radiotherapy can occasionally be classified as a medical device depending on their use. Specifically, if the phantom plays a key role in changing or deciding on patient's treatment, it may need to be considered a medical device. This leads to the question about where image quality and dosimetry 3D printed phantoms will fit in the context of the medical device directive. However, as this issue is focused on the individual use of the 3D printed phantom, it is beyond the scope of this paper to give advice.

Another interesting take from this data is the use of both freeware and commercial software for the creation of bolus. The medical device regulation [25], discusses the use of medical software and hardware in the clinic in depth. The development of 3D-printed phantoms demonstrates that some needs aren't being met with commercial phantoms. Without further information, it's challenging to determine if this comes down to financial constraints, the range of phantoms available or the desire to make phantoms more adaptable to the individual needs of a department.

In relation to the medical device regulation, there is a difference between custom-made devices produced in-house and devices manufactured in mass by companies. Custom-made in-house bolus needs a thorough quality management system, but the data here shows a lack of consistency for how that is being implemented.

There are known differences between filaments and printers and the

final product based on which one is used. Even wear and tear on the printer can lead to differences in the printed product. In spite of this, some departments weren't doing post print QA on every printed object, including bolus. Further studies into QA and QC could help identify the exact nature of post print QC needed to ensure accuracy.

The variation in risk management emphasises the need for guidance. Most departments were applying some risk assessment, however the risk assessments were varied and lacked the consistent approach that is normally seen in radiotherapy. A full risk management system should be in place prior to the introduction of any new technique or procedure. The QA procedures in place varied. It is clear from the data that centres using 3D printing for bolus are more inclined to have QA procedures in place and as bolus is placed directly on to the patient, this is expected. However, depending on how the phantoms are being used, there is a chance that they will have an indirect impact on patients' treatment. Validation of the phantom after the print is likely to be sufficient in cases where the phantom is designed in house with a specific goal in mind. In cases where the phantom print file has come from another centre or department with the idea of re-creating a phantom [26], the QA of the machine and having a structured system in place could help with centre variation of prints. This has demonstrated that the need for QA guidance is based on printer use. In one case a risk assessment hadn't been done as they hadn't gone clinical with the system yet.

There are some limitations to this study. The focus of the study was on UK and Irish centres and the overwhelming majority of respondents came from National Health Service (NHS) and Health Service Executive (HSE) hospitals (public hospitals). This could mean that this study doesn't reflect international trends in the area. Another limitation is that there were limited responses and that there may be bias based on why people respond to the survey. However, these should be negated by the fact-based nature of the questions being proposed and the high response rate achieved. In a future survey, there would be benefit from more details on the QA programs. Specific details on how the tests are performed, the tolerances applied and the ways that they reached those tolerances should be incorporated into future questionnaires. More information differentiating the QA requirements for different applications could help users understand how much time investment is needed to run a clinical 3D printer. The information presented here creates an initial base, however a more structured set of recommendations for QA and how they apply to each application would be beneficial to future users.

Overall, this study shows that there are currently exciting developments happening in 3D printing in the radiotherapy environment. The primary focus appears to be on phantoms, which could open up a realm of possibilities for the development of equipment for technique development and verification.

5. Conclusion

The results from this survey show that clearer guidance would be beneficial. The main use is for the production of radiotherapy phantoms. However, the introduction of commercial 3D printing software for bolus productions, as well as the influx of papers discussing the benefits of using 3D printed bolus, means that these could emerge as a major application within radiotherapy.

Implementation of 3D printing is varied. This may represent a problem with departments not knowing how to implement the technology. This highlights a need for a white paper or guidance to try and unify approaches. There would also be value in guidance that addresses how to comply the Medical Device Directive (MDR) and Health & Safety Executive guidance.

The high response to the survey, the variety of uses stipulated by the respondents and the increasing numbers of publications on this topic shows that there is a lot of excitement and development in this topic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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