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3-D Printing Dosimetry in Radiation Oncology: An Updated Systematic Review

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Abstract

Objective: This review presents a recent progress in the application of three-dimensional (3D) printing to dosimetry in radiation oncology**.** ***Methods:*** A thorough search across four databases identified 601 relevant publications. After removing duplicates using Rayyan QCRI and screening for relevance, 52 full-text articles were reviewed and six met the eligibility criteria for evidence synthesis. ***Results:*** The review covered six studies, including 76 cancer patients in total, of whom 52 (68.4%) were females. The studies indicated that 3D-printed boluses improved dose accuracy, skin conformity, and toxicity management during postmastectomy chest wall radiation. For scalp malignancies, integrated bolus/headrests minimized air gaps and enhanced treatment reproducibility. Customized boluses for squamous cell carcinomas (SCCs) in the extremities were adapted to anatomical variations, thereby increasing precision. Tongue immobilization devices reduced mucosal exposure in patients with nasopharyngeal cancer, outperforming standard mouthpieces. Patient-specific phantoms refined dose calculations, whereas 3D-printed nose boluses enabled cost-effective, highly controlled nasal cancer treatments with low toxicity. ***Conclusion:*** 3D printing is transforming radiation oncology by enhancing precision, personalization, and clinical performance. It addresses key challenges, such as dose conformity, reproducibility, and patient comfort. Despite its limitations, the benefits of 3D printing emphasize its future role as a vital tool in radiation therapy.

Keywords: 3D printing; radiation oncology; radiotherapy; radiation planning; clinical performance; systematic review.

1. INTRODUCTION

Using a range of standard materials, three-dimensional (3D) printing is an additive manufacturing (AM) technology that can be used to create customizable 3D items. 3D printing is becoming increasingly integrated into medical practice and innovation owing to its commercial availability and versatility [1]. It has been applied in a wide range of fields, ranging from therapeutic medical devices [2] to training and education [3]. In addition to being a low-cost substitute for conventional material manufacturing techniques, 3D printing can be used to create patient-specific models that may not otherwise be easily accessible [4, 5]. Furthermore, 3D printing facilitates the fabrication of intricate geometries that cannot be achieved with other methods such as injection molding or milling.

A recent development involves the utilization of patient imaging data to design phantoms using AM as a substitute for conventional methods for fabricating RPs (Radiotherapy Patient System) using molding and casting [6]. AM processes work through layer-by-layer printing, progressing from simple to complicated structures. Low-cost, patient-specific RPs that are viable can be produced with this method. Numerous studies have shown that AM technology [7] may be used to fabricate a variety of radiotherapy devices, including boluses, immobilization tools [5-8], brachytherapy molds [9], electron-beam cutouts [10], and compensator devices – in addition to imaging and dosimetry phantoms [11]. AM technology also has surgical and pharmaceutical applications [12].

Advances in 3D printing have thoroughly modernized the landscape of radiation oncology by offering novel ways of improving dosimetric accuracy, patient-specific treatment planning, and bolus personalization. Traditional methods of dosimetry and radiotherapy delivery cannot replicate complex anatomical geometries; consequently, they carry the risk of potential inaccuracies in dose distribution. 3D printing addresses these concerns by enabling the manufacture of anatomically correct patient-specific phantoms, boluses, and immobilization devices that improve the accuracy of radiation delivery. The rapid evolution of this technology requires frequent systematic reviews of the literature with respect to recent developments, applications, and clinical outcomes associated with 3D printing in radiation oncology. Accordingly, this review sought to summarize the current literature, identify the knowledge gap, and indicate the role of 3D printing in improving dosimetry practices in the future.

In summary, the aim of the present systematic review is to present an updated overview of recent progress in the application of 3D printing to dosimetry in radiation oncology.

2. METHODS

2.1 Search strategy

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) and GATHER (Guidelines for Accurate and Transparent Health Estimates Reporting) criteria were followed for the systematic review. An overall search was conducted to identify relevant studies related to the application of 3D printing for dosimetry in radiation oncology. The following four electronic databases were searched: SCOPUS, Web of Science, Cochrane, and PubMed. We included controlled studies published within the years (2019-2024). The search query incorporated the following keywords: "3D printing," "three-dimensional printing," "rapid prototyping," "radiation oncology," "radiation therapy," "dosimetry phantoms," "dosimetric phantoms," "treatment phantoms," "quality assurance phantoms," "anthropomorphic models," "patient-specific models," "human-mimicking phantoms," "cancer treatment," "tumor targeting," "carcinoma models," and "tumor-mimicking."

We removed duplicates and uploaded all titles and abstracts found through electronic searches onto Rayyan. Subsequently, all studies that met the inclusion criteria based on the abstract or title were assembled for a full-text examination. Two reviewers independently evaluated the suitability of each of the extracted papers and discussed any discrepancies.

2.2 Study population—selection

The PICO (population, intervention, comparator, and outcome) [13] factors were implemented as inclusion criteria for our review. The first three of these factors were implemented as follows: (i) our population consisted of patients undergoing radiation therapy for various cancers, including carcinoma and tumors, as well as oncology professionals involved in radiotherapy planning and quality assurance; (ii) our intervention consisted of the use of 3D printing technologies to create patient-specific dosimetry phantoms, custom boluses, anthropomorphic models, and quality assurance tools aimed at enhancing radiation treatment accuracy; and (iii) our comparisons consisted of conventional dosimetry methods (such as standard boluses), pre-fabricated phantoms, and traditional immobilization devices. Finally, the primary outcomes we assessed were improvements in radiation dose precision, reduction in radiation exposure to healthy tissues, enhanced customization of treatment planning, and overall improvements in patient safety and treatment efficacy.

2.3 Data extraction

Data from studies satisfying the inclusion requirements were extracted by two objective reviewers using a predetermined and uniform methodology. The following information was retrieved and recorded: (i) first author, (ii) year of publication, (iii) study design, (iv) country, (v) sample size, (vi) age, (vii) gender, (viii) cancer type, (ix) radiation oncology component, (x) intervention, and (xi) key findings.

3. RESULTS

The specified search strategy yielded 601 publications (Figure 1). After removing duplicates (n = 280), 321 trials were evaluated based on title and abstract. Of these, 266 failed to satisfy the eligibility criteria, leaving fifty-two full-text articles for a comprehensive review. Six of these articles satisfied the requirements for eligibility with respect to evidence synthesis. These six studies were analyzed for this review.

3.1 Sociodemographic and clinical outcomes

The six studies included a total of 76 cancer patients, of whom 52 (68.4%) were females. One study was a preclinical study [15], three of the six were case-series studies [16-18], one was an experimental study [19], and one was a retrospective study [20]. Two studies were conducted in the USA [15, 16], two in Korea [17, 18], one in Japan [19], and one in Canada [20].

These studies, covering diverse aspects of radiation oncology, predominantly focused on the use of boluses and immobilization devices to increase the precision and effectiveness of radiotherapy (RT). Some of the studies discussed patient-specific 3D-printed boluses for the chest wall, scalp, and extremities, including cancers of the nasal region, with respect to optimization of dose delivery [15-20].

Cancer diagnoses varied among the discussed studies, covering the following five types of cancer:

- Breast cancer: Personalized boluses in postmastectomy chest wall radiotherapy provided an example of accurate dose application. [15, 19]
- Scalp and neck malignancies: Radiotherapy for posterior scalp tumors was performed with a

3D-printed integrated bolus/headrest to reduce air gaps and improve treatment consistency [16].

- Squamous cell carcinoma (SCC): Personalized boluses were designed for radiotherapy of SCC in the distal extremities [17].
- Nasopharyngeal cancer: Tongue immobilization devices lessened mucosal radiation exposure when treating nasopharyngeal carcinoma [18].
- Cutaneous nasal carcinoma: A 3D-printed nose block bolus was used for delivering accurate radiotherapy for non-melanomatous skin cancer in the nose [20].

3.2 Main outcomes

One study indicated that 3D-printed boluses were effective in postmastectomy chest wall radiation therapy for breast cancer, emphasizing that those boluses could deliver precise radiation doses, ensure better skin conformity, and manage acute skin toxicity [15]. This result underlines the clinical value of 3D printing for optimizing dose distribution and minimizing complications during treatment.

A 3D-printed bolus integrated with a headrest provided the most critical component for reducing the risk of large air gaps in the treatment of posterior scalp malignancies, while offering a stable, repeatable, and comfortable setup for patients. This not only enhanced the accuracy of treatment, but also the experience of the patient during radiotherapy, which is an important consideration in ensuring consistency across multiple sessions [16].

In patients with SCC of the distal extremities, a tailored 3D-printed bolus overcame some of the limitations of conventional bolus designs. The associated study demonstrated that adapting the bolus to individual anatomic structures increased treatment accuracy and clinical efficacy in clinical use [17].

For nasopharyngeal cancer, the application of 3D printing in developing a device for immobilizing and displacing the tongue greatly reduced radiation exposure to the oral and oropharyngeal mucosa. Compared to standard mouthpieces, this semi-personalized device allowed for visual verification and improved reproducibility in radiotherapy, presenting a practical solution that improved treatment outcomes while minimizing toxicity [18].

Another study investigated the use of patient-specific 3D-printed anthropomorphic phantoms for breast cancer dosimetry. The results indicated that 3D conformal radiation therapy allowed phantoms to model the anatomy of the patient precisely, leading to improved dose calculation and the accurate delivery of radiation in a valid and reliable manner [19].

Finally, the use of 3D-printed nose block boluses in radiotherapy has proven to be effective and inexpensive for the treatment of non-melanomatous cutaneous carcinoma of the nose. This modality, in combination with optical scanning and orthovoltage beams, leads to a high degree of control with minimal toxicity, thus highlighting the value of personalized 3D-printed devices in the management of head and neck malignancies [20].

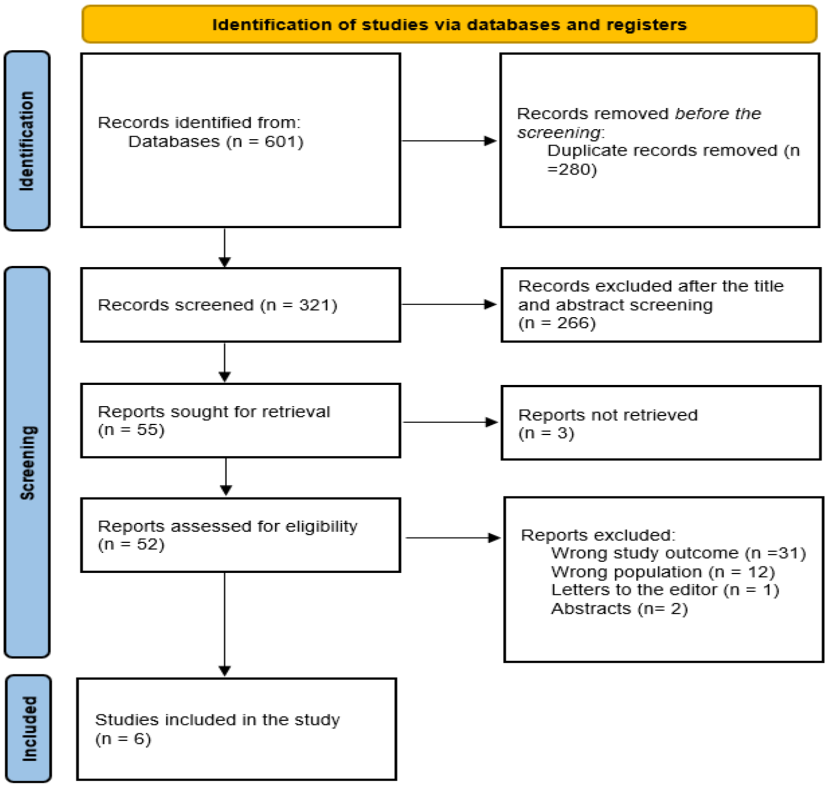

Figure 1: PRISMA flowchart [14]

Table 1: Outcome measures of the included studies

Study ID	Study design	Country	Sociodemographic	Cancer type	Component of radiation	Intervention	Main outcomes
Wang *et al.*, 2022 [15]	Preclinical study	USA	Cases=27 Mean age: 49 Females: 27 (100%)	Breast cancer	Bolus	The design, fabrication, and application of patient-specific 3D-printed boluses for chest wall radiotherapy in post-mastectomy patients.	3D-printed boluses are highly valuable in postmastectomy chest wall radiation therapy for breast cancer, as they provide precise skin surface dose delivery, ensure a better fit to the skin, and help manage acute skin toxicity.
Hsu *et al.*, 2022 [16]	Case series	USA	Cases= 5 Age range: 39-90 Females: 1 (20%)	Scalp and neck malignancies	Bolus	This intervention combines surgical resection, adjuvant radiation therapy, and the potential for chemotherapy	A custom 3D-printed integrated bolus/headrest is beneficial in radiotherapy for posterior scalp malignancies, as it reduces the risk of large air gaps and ensures a comfortable, consistent, and repeatable treatment setup.

Cheng *et al.*, 2022 [20]	**Endarko *et al.*, 2023 [19]**	**Ju *et al.*, 2021 [18]**	**Yu *et al.*, 2023 [17]**
Retrospective cohort	Experimental study	Case series	Case series
Canada	Indonesia	Korea	Korea
Cases= 26 Mean age: 78.5 Females: 15 (42%)	Cases= 6 Females: 6 (100%)	Cases= 10 Age range: 39-62 Females: 2 (20%)	Cases= 2 Age range: 66-68 Females: 1 (50%)
Cutaneous nasal .	Breast cancer	Nasopharyngeal cancer	SCC
Bolus	Quality assurance phantoms	Immobilization device	Bolus
The use of customized 3D-printed nose block boluses to deliver radiotherapy for patients with non-melanomatous cutaneous carcinoma of the nose.	Direct dose measurements using 6 MeV single-beam 3D-CRT were performed on a patient-specific 3D-printed phantom, with the treatment planning system ensuring accurate dose calculation and precise delivery.	The design, fabrication, and application of a tongue immobilization and displacement device for reducing radiation dose to the oral cavity and oropharyngeal mucosa during radiotherapy.	The design, fabrication, and application of customized 3D-printed boluses for radiotherapy treatment of SCC in the distal extremities of two patients.
A successful and economical method for treating nasal cancers with a high control rate and low toxicity profiles is facilitated by the use of optical scanners, 3D printing, and the novel technique of parallel opposing orthovoltage beams.	A patient-specific 3D-printed anthropomorphic phantom for breast cancer following a right-side mastectomy offers an alternative for determining radiation therapy dosage.	When compared to a regular mouthpiece, a semi-customized tongue immobilization device can significantly lower the dose to the M-tongue while simultaneously offering superior reproducibility and simple visual verification.	A novel type of personalized 3D-printed bolus mitigates the drawbacks of traditional boluses for radiotherapy for skin cancer in the distal extremities. Its effectiveness was assessed by using it in clinical settings.

4. DISCUSSION

To the best of our knowledge, this study is the most thorough systematic review to date that details the use of 3D printing in radiation oncology. This review provides a reference for practitioners and academics that will facilitate the integration of 3D printing technology into their regular practice because of the formal characterization of existing 3D printing treatments and the identification of common obstacles to their safe and successful implementation. Dosimetric research and small-sample clinical evaluations suggest that most of the proposed modifications have successfully improved therapy delivery; accordingly, there are many intriguing potential applications for the use of 3D printing in radiation oncology clinics or laboratories. Further research is required to verify the effectiveness of these therapies in more extensive clinical settings.

The studies included in this review focused on 3D-printed boluses and immobilization devices to improve the precision of radiotherapy. Patient-specific boluses enhance dose delivery for chest wall, scalp, extremity, and nasal cancers, whereas immobilization tools such as tongue displacement devices protect critical structures and reduce radiation exposure. These characteristics may be ascribed to the fact that 3D printers can create patient-specific models at relatively low cost, which is one of the main advantages of 3D printing compared to more conventional material fabrication techniques such as casting or molding [21]. The use of customized models for boluses, brachytherapy applicators, and quality assurance phantoms can enhance treatment delivery and reduce needless toxicity [22]. For instance, 3D-printed boluses can minimize therapy delivery errors by conforming more closely to the patient's skin than standard boluses [23].

We have demonstrated that 3D printing applied to radiation oncology results in improved accuracy and personalized treatment. The inherent anatomic variability of 3D-printed boluses and immobilization devices facilitates the improvement of dose conformity, thus reducing the exposure of normal tissues to unnecessary radiation. The risk of air gaps is reduced, and reproducibility in successive treatment sessions is enhanced. This is a very important factor in maintaining consistency in complex cases such as scalp and nasopharyngeal cancers. In addition, a high level of competence in the fabrication of customized phantoms for dosimetric validation enhances the precision of radiation delivery, ultimately leading to improved clinical outcomes. In an earlier systematic study [24], Rooney *et al.*, provided a thorough description of existing applications of 3D printing in radiation oncology and identified frequent obstacles to the successful adoption of the technology. Three-dimensional (3D) printing methods have increasingly been used in radiation oncology for various applications, revealing exciting new possibilities for innovation in the field. However, there is a dearth of information assessing the clinical safety and effectiveness of these therapies, and further research is required to enable their widespread adoption.

Conti *et al*., reported that although radiation oncology is not usually considered a procedurally demanding discipline, the use of 3D printing in training could be beneficial. For example, complex arteriovenous malformations (ATMs) can be visualized during radiosurgical treatment planning by using 3D-printed patient-specific models [25]. Specifically, 3D printing of patient-specific organs or tumors could potentially aid trainees in visualizing intricate anatomical linkages as they learn about contouring.

The dearth of literature on practical methods for applying 3D printing technology in laboratories and clinics constitutes another significant gap that we identified in the present review. Few publications have specifically outlined strategies for instructing providers in the use, design, and assessment of 3D printing applications, notwithstanding the fact that numerous studies have recognized the necessity of sufficient competence in 3D printing techniques if consistent levels of accuracy are to be achieved in interventions [26, 27].

There are several obvious clinical benefits associated with the use of 3D printing technology in radiotherapy, including improved treatment accuracy and comfort for the patient, and a reduction in side effects. Custom-made boluses for postmastectomy and extremity tumors permit effective radiation doses to be delivered, thus reducing skin toxicity and improving therapeutic outcomes. Similarly, immobilization devices for patients with nasopharyngeal cancer reduce the risk of mucosal damage, addressing a common source of treatment-related complications. Increased access to 3D printing and its more pervasive clinical adoption would ensure higher standards of personalized care that would optimize cancer treatment pathways.

5. Strengths

This review represents an in-depth integration of recent progress in 3D printing in radiation oncology and covers a range of cancer sites and types. The review provides a broad range of information that clarifies how 3D printing bolsters precision in treatment and patient outcomes by considering studies on boluses, immobilization devices, and phantoms. Furthermore, it provides perspectives on optimizing the provision of personalized medicine to patients in the field of radiotherapy and provides valuable insights into growing trends in clinical practice.

6. Limitations

This review may be constrained by the limited generalizability of its content owing to the heterogeneity of the included studies in terms of methodologies, sample sizes, and types of cancer. Most of the studies did not present long-term outcome data; consequently, it was not possible to assess the durability and effectiveness of the 3D-printed devices over a long period. This review may also be subject to publication bias, because smaller studies or datasets have not been published. The evolving nature of this technology means that recent developments in 3D printing may not be included in the literature; as a result, the review may not apply comprehensively to current clinical practice.

7. CONCLUSION

3D printing has become a game-changing tool in radiation oncology. It provides improved precision and personalization and has a positive impact on clinical performance. 3D printing technology answers various prominent challenges of radiation oncology: dose conformity, reproducibility, and patient comfort. These advantages outweigh the limitations of the technology and indicate that 3D printing will be a significant tool for radiation therapy in the future.

Data Availability Statement: All data is available in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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