The Use of Three-Dimensional Printed Bolus in Radiation Oncology: A Literature Review

**Abstract**

**Background:** Although three-dimensional printing was a technology initially designed for the engineering field, but it was quickly adopted by other organizations. The medical field is incorporating this technology more frequently into practice due to some notable benefits to employees and patients.

**Objectives:** The purpose of this paper is to review research on the use of three-dimensional printing in radiation oncology. Advantages and disadvantages of utilizing three-dimensional bolus will be explored.

**Methods:** Peer reviewed articles were gathered and analyzed through search engines such as EBSCO host and MEDLINE. Restrictions were placed to ensure accurate information.

**Results:** Three-dimensional bolus is created through the manipulation of imaging data sets. It can be created to mimic certain qualities of conventional forms of bolus such as SuperFlab and wax materials. Treatment planning systems allow bolus to be customized for each patient to ensure proper fit and eliminate unwanted qualities of conventional bolus. Three-dimensional material has been shown to deliver dose in similar ways as conventional bolus. There are concerns when determining properties such as density and appropriate Hounsfield numbers.

**Conclusions:** The use of three-dimensional bolus has many positive qualities associated with its use. Quality of care delivered in radiation oncology could be improved by replacing conventional bolus with three-dimensional bolus. Multiple studies have shown the advantages of using three-dimensional bolus on both patients and phantoms. There is current literature on disadvantages of the material in radiation oncology too. More research is needed to further define the benefits of using three-dimensional bolus in an oncology setting.

**Introduction**

 The concept of three-dimensional (3D) printing was first invented in the 1980’s by a man named Charles Hull.1 Hull created this technology with the intent to model prototypes for the engineering and industrial fields.1 The technology quickly caught the attention of many other scopes of practice, including the medical field.1 Since its creation, the capability of 3D printing has advanced dramatically.1-3 Specifically focusing on the medical field, 3D printing is used largely to study complex patient cases, educate and train future medical workers, and produce custom prostetics.1-3 Health care departments including cardiovascular, plastic surgery, orthopedics, neurology, and radiation oncology have utilized 3D printing for various products.1-3 Recent data shows the purchasing of 3D products in the medical field has seen a 27 percent growth rate between 2010 and 2012.2 The recent growth may be attributed to reports of increased accuracy of treatment planning, improved understanding of complex cases, reduced surgical operation times, and increases in patient understanding of treatment approaches by hospitals using 3D products.1-3

 The scope of this paper is a review of literature on the use of 3D printing in the field of radiation oncology, specifically for the production of bolus. 3D printing and its presence in the health care field will be discussed. The advantages of 3D bolus over the predominant forms of bolus used in the field will be stated, as well as the disadvantages. The paper will focus on aspects such as dose delivery, design, clinic feasibility, and accuracy. It is important for radiation therapists to know the principles of 3D printing and be able to understand how these principles can apply to the field of radiation oncology. Therapists should be able to identify both the positive and negative implications 3D technology incorporates into their job.

**Methods**

A literature review was conducted to examine the practicality of three-dimensional bolus in radiation oncology. Peer reviewed articles were obtained through the use of the Academic Search Ultimate (EBSCO) host and the National Library of Medicine (MEDLINE). Searches were conducted between December 2018 and February 2019. To keep the review concise, a combination of vocabulary terms were used to gather research. These terms included “radiation therapy”, “radiotherapy”, “3D”, “three-dimensional”, “printing”, “bolus”, “material”, and “clinical applications”. To ensure the information was current, reliable, and relevant, filters were applied that included “Full Text” and “Academic Journals”. Additionally, articles published before 2014 were excluded.

**Literature Review**

 **The concept of 3D bolus**

Bolus is primarily used to reverse the skin sparring effects of photon radiation and bring dose closer to the surface of the skin. Superficial lesions can be targeted more effectively through the use of bolus. Bolus takes on many different forms depending on the facility at which it is being used. The most common types of bolus being used in today’s oncology department are SuperFlab, brass mesh, wax, or wet towels.4 While these materials have proved to shift the dose of radiation closer to the surface of the skin, variations to the treatment plan are also introduced due to subtle changes in placement, formation of air gaps, and inconsistent production of material.4,5 To improve uniform dose distributions and increase the accuracy of patient set-up, 3D bolus was introduced into the field of radiation oncology.5 The use of 3D bolus aims to diminish variations introduced to the treatment plan by eliminating the human fabrication process.5 Bolus created with 3D technology uses images of the planned target volume to maximize accuracy.5

**Creation of 3D bolus**

The creation of a patient specific bolus is through the manipulation of material such as SuperFlab or wet gauze and is typically done by a radiation therapist under the supervision of an oncologist. With the use of 3D technology, hospitals are offered the option of producing bolus that is manipulated by adding material together via data from 2D image sets.1 The 2D image sets are usually in the format of a computed tomography (CT) scan or magnetic resonance image (MRI) scan.1,2 These images are stored in a Digital Imaging and Communications in Medicine (DICOM) format and need to be converted to a Standard Tessellation Language (STL) format to be compatible with a 3D printer.2 Printers need these files because DICOM files are unable to communicate with 3D hardware.2 The conversion from DICOM to STL files allows geometric information to be conveyed between the computer and printer in an accurate 3D manner.2 The STL images are segmented by oncologists and planning teams to define objects of interest for the bolus to match.2 A 3D product can be crafted once the STL file is exported to the printer.2

Formation of bolus can be achieved by three major printing methods: liquid-based, solid-based, and powder based.1,2 Further yet, the main categories can be broken down into five subcategories.1,2 These subcategories are vat photopolymerization, material jetting, binder jetting, material extrusion, and powder bed fusion.2 Vat photopolymerization and material jetting fall under liquid based 3D printing.2 The printers utilize light sources, such as a laser or UV light, to transform ink or liquid resin into solid material.2 The binder jetting method is categorized as a powder 3D printing method.2 The method uses a liquid and powder agent to form a solid material.2 Material extrusion and powder bed fusion are labeled as a solid based 3D print method. Solid input such as plastic, polymer, metal, and ceramic are used to shape a 3D product.2

**Common 3D bolus materials**

Just as there are different ways to print 3D bolus, there are also different materials that can be used to form the final product. The most common materials used for 3D radiotherapy bolus are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA).4 Additional materials that have been approved for the use of bolus in radiotherapy include thermoplastic polyurethane (TPU) and polyvinyl acetate.4 Each of the four materials have been validated to share similar properties to water.4 Knowledge of material makeup allows for accurate representation in treatment planning systems designed for photon and electron beams.4

The material of 3D bolus has been highly researched for dosimetric properties, reproducibility, and patient comfort.4-11 There is evidence which suggests ABS and PLA bolus can produce a measured dose within a half of a percent of the calculated treatment planning dose.4 Materials such as ABS and PLA are rigid in structure which could be problematic for any changes in anatomy over the course of treatment.4 Further research6 has been conducted to explore the use of silicone material due to its flexible nature. Chiu et al.6 treated seven head and neck cancer patients with silicone bolus which was produced using a casting mold with 3D printing. The material showed less than five percent deviation of the prescription dose and had high conformity to the patient’s anatomy.6

 **Comparison of bolus**

To analyze the need for incorporation of 3D bolus into radiation therapy, there must be clear advantages over the current methods used in the field. One of the main attractions of 3D bolus is the ability to have customized pieces for individual patients that are non-uniform.7 Conventional forms of bolus, such as SuperFlab, limit physicians to the option of using a uniformed piece of bolus.7 When applied to anatomy, such as reconstructed breasts with spacers, dosimetric accuracy is reduced and errors in treatment dose can occur.7 With the use of 3D printing, differences in anatomy can be accounted for through the use of CT images.7 The printer will adjust the material for each patient’s anatomy and create thicker and thinner areas where necessary.7 This capability allows for individualization of each treatment plan and could lead to variations in dose build-up on the same patient in different locations on the bolus.7

Through this differentiation, 3D technology has also been shown to reduce the amount of air gaps formed under bolus.7 Air gaps are a direct result of bolus that is not adhered tightly to the skin. Air gaps cannot be predicted during treatment planning resulting in a dose shift to the skin causing discrepancies in the calculated verse measured dose.7 In a study conducted by Robar et al,7 16 postmastectomy chest wall radiation candidates were fitted for both a five-millimeter SuperFlab and five-millimeter 3D printed bolus. Bolus was altered between the two types to determine if 3D bolus provided a more consistent fit.7 The study7 concluded that there was a significant difference between the two materials. On SuperFlab days, an average of 30 percent of fractions included a larger than five-millimeter air gap between the patient and bolus compared to 13 percent on 3D bolus days.7 Overall, 3D printed bolus resulted in fewer total air gaps.7 SuperFlab, when compared to 3D bolus, showed the most problematic areas of air gaps in anatomy that was convex or concave in nature.7

 Air gaps are one issue 3D bolus aims to eliminate, but to be effective, the material must demonstrate other properties that make treatment planning optimal. Another major comparison standpoint of 3D verse conventional bolus is whether or not the material printed can depict human tissue.8 Human tissue has similar properties to water.8 Bolus must possess the same properties due to the effects of Compton interactions.8 Compton interactions are the most prevalent in the energy range used for photon external beam radiation and can result in unwanted absorbed dose to a patient.8 A material that interacts with radiation much like the human body can be more accounted for and help determine or manipulate the dose.8 The conventional forms of bolus currently used in radiation therapy possess these properties, making them ideal for dose calculations.8

In a study conducted by Burleson et al8, 3D bolus was shown to be able to achieve comparable properties to water and conventional forms of bolus. Bolus made out of ABS and PLA were printed and the physical properties were analyzed.8 Analyzation was completed by measuring the tissue maximum ratio (TMR) using an ion chamber.8 The TMR curves for each 3D bolus was compared to TMR curves for water, wax bolus, and SuperFlab.8 The study8 showed ABS was the most similar to that of water, in regards to electron density, physical density, and effective Z values. The PLA bolus differed the greatest in its electron density and physical density when compared to water.8 The differences resulted in a percent depth dose (PDD) curve that varied from that of a water phantom.8 The PLA PDD curve exhibited a faster buildup to the dose maximum and then had a steeper fall off region.8 The PDD curve differences stayed consistent when tested with different energies of photon and electron beams.8 The data indicates that ABS bolus can be considered water equivalent in treatment planning systems and be assigned the same Hounsfield numbers.8 If Hounsfield numbers are altered to account for the differences in physical properties, PLA material is still a viable 3D bolus material.8

Research8 has shown 3D bolus can mimic the physical properties of conventional bolus and provide better fit to patients. Another consideration is whether or not 3D material can provide similar dose distributions to the patient. One study8 used a PLA bolus with a corrected Hounsfield number of 260 to test the accuracy of dose in 3D bolus. The bolus was tested at various thicknesses and compared to wax and SuperFlab bolus.8 Bolus was placed on a RANDO phantom and irradiated with 9 MeV electrons at 105 source to skin distance (SSD).8 Dose distribution information was collected using exposed Gafchromic EBT2 film.8 The films were compared to the calculated doses designed in a treatment planning system.8 Exposed film showed less than five percent difference in isodose curves for the measured verse planned doses.8 The study8 also included optically stimulated luminescent dosimeters which read within a half percent of the calculated verse measured dose.

Kim et al9 conducted similar research on RANDO and Blue water phantoms. Treatment plans were created for the phantoms for non-bolus, SuperFlab bolus, and a ABS 3D printed bolus.9 Factors such as monitor units, field size, SSD, and energy of the beam were kept consistent throughout the three plans.9 Dose at the central axis was measured using a farmer ionization chamber.9 The data collected showed a less than one percent difference in measured verse calculated dose at different depths in the SuperFlab and 3D bolus.9 Furthermore, values such as the mean dose, minimum dose, and volume that receives 90 percent of the prescribed dose all were sufficient compared to the planned values.9

**Clinical implications**

Data4-10 supports that 3D bolus can physically mimic that of conventional bolus and provide the same dose benefits. Studies10 have also looked into the clinical impact of incorporating 3D bolus into the workflow. The cost of instituting 3D bolus, the amount of time it takes to create the product, and the staff intervention needed are all considerations of adapting 3D bolus into the workplace.10 In a study10 conducted at the University of Minnesota the average 3D bolus generation time was calculated in 14 cases by including parameters such as segmentation of CT images, conversion of DICOM files to STL files, and print time.The 14 types of bolus varied by tumor location and size but on average took approximately six hours to create from start to finish.10 When factors such as the diameter of the printing nozzle was changed, printing times were decreased.10 Several studies4,6,10 have concluded that a customized bolus can be crafted from start to finish within one day.

Cost is also a consideration for departments when implementing new procedures. There are two costs associated with 3D printing, the cost of the printer and the cost of the material.2,3,6,10 Printers can range greatly in price.2,3,6,10 Current research2,3,6,10 puts the startup cost of printers from hundreds to thousands of dollars.Material for the printer is around one hundred dollars per kilogram.2,3,6,10 A cost saving measure of 3D printing allows hospitals to use the same material to print different thicknesses of the product, whereas different thicknesses for products like SuperFlab would need to be purchased individually.5 Hospitals can also invest in products that can be reimbursed by insurance companies as there are now billing codes for 3D printed devices.5

Staff intervention is another component that hospitals need to consider when deciding whether or not to incorporate 3D printing into the department. Conventional forms of bolus are typically created during the simulation CT and require staff members to assemble the entire product. The use of 3D printing can cut back on the amount of time staff spends working with bolus.4,5,10 If prior CT image sets have been taken of patients that require bolus, the physician can start to plan and create the bolus prior to the patient arriving at simulation.4 The bolus can then be scanned at the time of simulation to ensure proper fit to the patient and determine if there are any structural flaws in the material.4 Staff needs to occasionally check in on the 3D printer to ensure the product is being formed adequately.4,10 Issues with the product detaching from the printer bed have been documented, indicating need for staff mediation.4,10

**Limitations of 3D bolus**

3D bolus does an effective job at eliminating air gaps, providing similar dose distributions to that of conventional bolus, and capitalizing on staff efficiency, yet there is also evidence for imperfections in 3D bolus too.8,11 These drawbacks include variation in materials and printers, inaccurate density modeling, and structural concerns.8,11 Research suggests8,11 that the impact of these limitations can result in errors in delivery of treatment. Hospitals should be aware of the limitations to reduce the occurrence in potential errors.

Significant errors can result from inaccurate representation of 3D bolus in treatment plans.11 In an attempt to study the impact of incorrect density modeling, Craft et al11 printed four common bolus materials (PLA, ABS, NinjaFlex, and Cheetah) on the same 3D printer. The researchers found that when 10 cubes of each material were printed from the same manufacturer spool, the physical density varied between the cubes.11 The study11 further discovered that a standard CT calibration curve based on the material’s Hounsfield numbers could not predict the density of the cubes accurately.11 CT calibration curves are typically used to convert a material’s Hounsfield numbers to a physical density.11 The determined density is then used in a treatment planning system for planning purposes.11 The incorrect measurements, predicted by the curve in this study, resulted in the measured 90 percent isodose depth curve being 1.8 millimeters different compared to the calculated curve.11

Craft et al11 study indicated that 3D material cannot be assumed to be accurately modeled by a treatment planning system if the physical density is not known. Instead to ensure patient safety, each bolus printed may need to be physically assessed by the treatment planning team to verify accurate dose calculations.11 Quality assurance tests, which include CT scanning the bolus and physically measuring the density, may need to be incorporated into a clinic workflow.8,11 A hospital can physically measure the density of an object by using tools such as calipers and precision balances.11 Quality assurance measures can reduce the 90 percent isodose error to less than one millimeter.11

Assuming density values are correct, 3D bolus can also present issues in its structure. Common material such as ABS and PLA are often rigid and cannot conform to changes in patient anatomy.4 Patients undergoing courses of radiation therapy may experience changes in anatomy.4 The use of 3D bolus is designed to fit snugly against the anatomy at the time of simulation.4 If patients lose weight or have fluid buildup, the bolus may no longer fit the way it was intended to.4,7 Robar et al7 demonstrated this phenomenon when a participant developed a significant air bubble between the 3D bolus and the skin due to anatomical changes. The changes in the patient’s anatomy resulted in the bolus no longer fitting.7 Anatomical changes can be monitored throughout treatment course and 3D bolus has the ability to be reprinted with daily image guidance sets, such as cone beam computed tomography scans, collected during treatment.7

**Conclusion**

 In conclusion, 3D printing could make a large difference for cancer patients. Current research4-10 provides evidence that precise dose for cancer treatment is achievable through the use of 3D bolus. Furthermore, 3D bolus can provide additional benefits than that of conventional bolus by eliminating the formation of air gaps in treatment setups.7 Hospitals can deliver a higher quality of care to patients, at a reasonable startup cost and with reimbursement from insurance companies, by using 3D bolus.2,3,5,6,10 There are limitations that need to be addressed with 3D bolus such as differences in Hounsfield numbers and density calculation errors.4,7,11 Limited research is available regarding 3D bolus and actual patients. In the near future, research needs to shift from phantoms to live patients to demonstrate the true capabilities of 3D bolus. Further research should be conducted to explore the creation of less rigid 3D bolus and how to have more consistency in physical parameters for different 3D material. Additionally, TPS should consider updates to include formats that would work directly with 3D printers to cut out the conversion step between DICOM and STL files.

This literature review focused on the use of 3D printed bolus in radiation oncology. Current research was presented for the advantages and disadvantages 3D bolus can provide. This literature review is relevant to practicing radiation therapists, as they are the ones working directly with the creation and application of bolus. Therapists should educate themselves on the evolving forms of bolus because it provides an opportunity to be advocates for patients. Radiation therapists are on the frontline to push for the implementation of new technology such as 3D bolus to improve the precision of treatment and quality of care a hospital is providing. The use of 3D bolus can directly impact cancer patients by reducing harmful side effects and increasing their quality of life.

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