Development of a customisable 3D-printed intra-oral stent for head-and-neck radiotherapy

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ABSTRACT

Intra-oral stents (including mouth-pieces and bite blocks) can be used to displace adjacent non-involved oral tissue and reduce radiation side effects from radiotherapy treatments for head-and-neck cancer. In this study, a modular and customisable 3D printed intra-oral stent was designed, fabricated and evaluated, to utilise the advantages of the 3D printing process without the interruption of clinical workflow associated with printing time. The stent design used a central mouth-opening and tongue-depressing main piece, with optional cheek displacement pieces in three different sizes, plus an anchor point for moulding silicone to fit individual patients' teeth. A magnetic resonance imaging (MRI) study of one healthy participant demonstrated the tissue displacement effects of the stent, while providing a best-case indication of its comfort.

1. Introduction

Radiotherapy plays an important role in improving the outcomes for head-and-neck cancer patients [1–3]. Despite advances in treatment conformity due to the introduction of intensity modulated radiotherapy (IMRT) and volumetrically modulated arc therapy (VMAT), challenges remain in reducing radiation-induced toxicity to healthy tissues in the head-and-neck region [4–6]. The dose conformity achievable using IMRT and VMAT means that it is especially important to ensure that the position of the targeted tissue remains consistent, from planning to delivery of each treatment fraction, and that the target can be displaced from nearby sensitive tissues. During the course of radiotherapy, interfraction and intrafraction movement of structures within and surrounding the oral cavity may cause unintentional irradiation of healthy tissue, exacerbating radiation side effects such as oral mucositis, xerostomia, osteoradionecrosis, trismus, pain and dysgeusia [4,5,7], all of which have adverse effects on quality of life.

Intra-oral stents (including mouth-pieces and bite-blocks) have been increasingly implemented in head-and-neck radiotherapy, to immobilise oral structures and displace adjacent non-involved tissue away from the radiation beam and thereby reduce side-effects [7–9]. Intra-oral stents can produce reproducible jaw opening and tongue depressing effects for immobilisation and tissue sparing of the tongue, palate, maxilla, mandible and other nearby tissues [8,10]. For example, Appendino et al. demonstrated that a jaw opening, tongue depressing device, used in conjunction with VMAT, provides the ability to reduce mean dose to the mandible, parotid glands and most the oral cavity [5]. Reproducible cheek displacement is also desired in some patient cases to further immobilise oral tissues and ensure the buccal mucosa are outside of the high dose region [11,12].

Widely used methods for fabricating intra-oral stents for radiotherapy have involved either in-house fabrication using materials with questionable mechanical stability such as wax [12,13] or reliance on multiple dentistry appointments for design and fitting of more

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sophisticated patient-specific stents fabricated from resins [14–16]. Published commercial solutions have been limited to generic tongue depressors and mouth-opening wedges [17]. The limitations of these stents and stent production methods clearly provide an opportunity for potential implementation of a 3D printed solution.

There is growing interest in three-dimensional (3D) printing for radiotherapy applications due to the ease with which novel designs can be created and tested as well as the comparative affordability of 3D printers and non-toxic printing filaments [12,18]. However, the time needed to fabricate an immobilisation device [18], even something as small and comparatively low-density as an intra-oral stent [12], may be regarded as an obstacle to routine use of 3D printing in the radiotherapy treatment preparation workflow. For example, whereas an intra-oral stent can be molded from wax within 30 min before the patient is CT scanned with the stent in situ for treatment planning, fabricating an identical intra-oral stent using a fused deposition modelling (FDM) printing system may take as long as four hours [12], requiring the patient to return for a separate CT scanning appointment.

In order to leverage the many advantages of the 3D printing process, while minimising the negative workflow impacts of printing time, this study developed and evaluated a novel, ready-to-use 3D-printed intra-oral stent with customisable, modular components suitable for achieving the various tissue displacement requirements of contemporary head-and-neck radiotherapy.

2. Methods

A list of design requirements for the 3D-printed intra-oral stent was developed through consultation with a stakeholders group of clinical staff experienced in patient simulation, treatment planning and technical mould-room work (radiation therapists/radiation therapy technologists/dosimetrists, radiation oncologists, a physicist and a mould room technician). Specifically, the stent needed to: allow reproducible tongue depression and jaw opening, with/without cheek displacements of different magnitudes; allow patient-specific teeth impressions; be robust and unlikely to degrade over the course of treatment; be comfortable, cleanable and easy to use; and be inexpensive (for a department with a pre-existing in-house 3D printing programme). Based on these design requirements and a review of designs described in the literature, a modular design was proposed. An iterative process of design, prototyping, consultation and refinement was used to develop a design that addressed the stakeholder-identified design requirements.

3D design was undertaken using Autodesk AutoCAD 2020 (Autodesk, Mill Valley, United States) software. Designs were printed using two fused deposition modelling (FDM) systems: the Ultimaker 2 Extended+ (Ultimaker BV, Utrecht, Netherlands) and Raise3D Pro2 (Raise 3D Technologies, Irvine, USA). Printing instructions in g-code format were generated for the two printers using Cura (Version 4.3, Ultimaker BV) and ideaMaker (Version 3.4.2, Raise 3D Technologies), respectively.

Polylactic acid (PLA) was the chosen material for the main piece due to its biodegradability, biocompatibility and strength [19,20]. PLA has been used successfully in other radiotherapy applications [18,21] and has shown resistance to radiation damage [22]. Thermoplastic polyurethane (TPU) was the chosen material for the cheek displacement pieces, due to its flexibility, resistance to abrasion and ability to withstand impact [20]. TPU has previously been used for radiotherapy bolus due to the conformity of the material and the comfort it provides for patients [23]. During the designing process, consideration was given to smoothing edges for patient comfort, maintaining structural durability, designing easy to use connections and reducing bulk where possible.

The cleaning durability of the intra-oral stent was tested by weighing before and after cleaning, to determine whether any plastic was lost or any liquid was absorbed during cleaning. A sample 3D printed stent was assembled using all three pieces, weighed and then washed, rinsed and manually dried before being weighed again, further blow-dried for 60 s

and then weighed for a third time. The stent was then soaked overnight in the cleaning solution, before being weighed, manually dried, weighed again, blow-dried for 60 s and then weighed for a final time.

The degrees of mouth opening, tongue depression and cheek displacement produced by the modular 3D printed stent were evaluated simultaneously with comfort and stability using repeated magnetic resonance imaging (MRI) of a healthy volunteer. A healthy participant was used in this study to provide a best-case indication of comfort and stability so that any poor stent performance or particiant complaints could be used as a strong indication that the stent would be unsuitable for head-and-neck cancer patients, especially those with painful oral lesions or irregular anatomy.

T2-weighted turbo spin echo images were acquired with the participant lying supine with and without the 3D printed intra-oral stent in situ, with each image acquisition taking four minutes. For this study, the smaller main piece was combined with two medium sized cheek displacement pieces. Imaging was completed twice, with a 65 min gap between repetitions, to provide an indication of positioning reproducibility simultaneously with the degree of tissue displacement and the best-case indication of comfort. Resulting images were analysed using measurement tools in MIM Maestro software (MIM Software Inc, Cleveland, USA). This MRI imaging study was approved by the Royal Brisbane and Women's Hospital Human Research Ethics Committee (RBWH HREC, EC00172) and this study was completed in accordance with the ethical standards of the RBWH HREC and the 1964 Helsinki declaration and its later amendments.

3. Results

3.1. Design

There were eight iterations of design, analysis, stakeholder consultation and refinement to achieve the final intra-oral design. This final optimised design included a rectangular box-shaped main body, with tooth placement grooves on top, a breathing hole within, with the ability for modular insertion of different sized cheek displacement pieces to facilitate buccal mucosa sparing as well as tongue depression and jaw opening. The attachable cheek displacement pieces were designed to connect and disconnect from the main piece, stay firmly in the main piece when connected, pass between the top and bottom molars or premolars, and displace the cheek laterally.

The optimised main piece, shown in Fig. 1(a)-(d), had the following features: a rounded upper surface with a tooth-positioning slot; a smooth lower tongue-depressing lower surface; two lateral cheek displacement connection slots (Fig. 1(c)); a breathing channel; and a 20 mm long positioning tab.

To allow the main piece to be standardised and pre-fabricated while also allowing a patient-specific fit to the teeth, food-grade silicone was selected to mould to the incisors and the tooth positioning slot, as shown in Fig. 1(b).

The main piece was designed in two sizes, for small and large mouths, extending 30 mm and 38 mm into the mouth respectively (Fig. 1(a)). The jaw opening effect for both main piece sizes was designed to achieve a minimum of 22 mm, which could be increased by varying the thickness of the attached silicone layer. Each cheek displacement connection (Fig. 1(c)) consisted of a $13 \times 8 \times 5$ mm^3 rectangular excision, with 1.5 mm radius half spheres cut out on the front and back ends to act as anchor points. The breathing channel (visible in Fig. 1(d)) consisted of an 8 mm high and 10 mm wide cut out passing through the length of the main piece. The support tab (thin section at the left hand side of the main piece in Fig. 1(a) and (b)) would be located outside the patient's mouth and allow easy placement and retrieval of the stent. Integrated support brackets were added between the positioning tab and the main body to strengthen the connection to the comparatively thin tab.

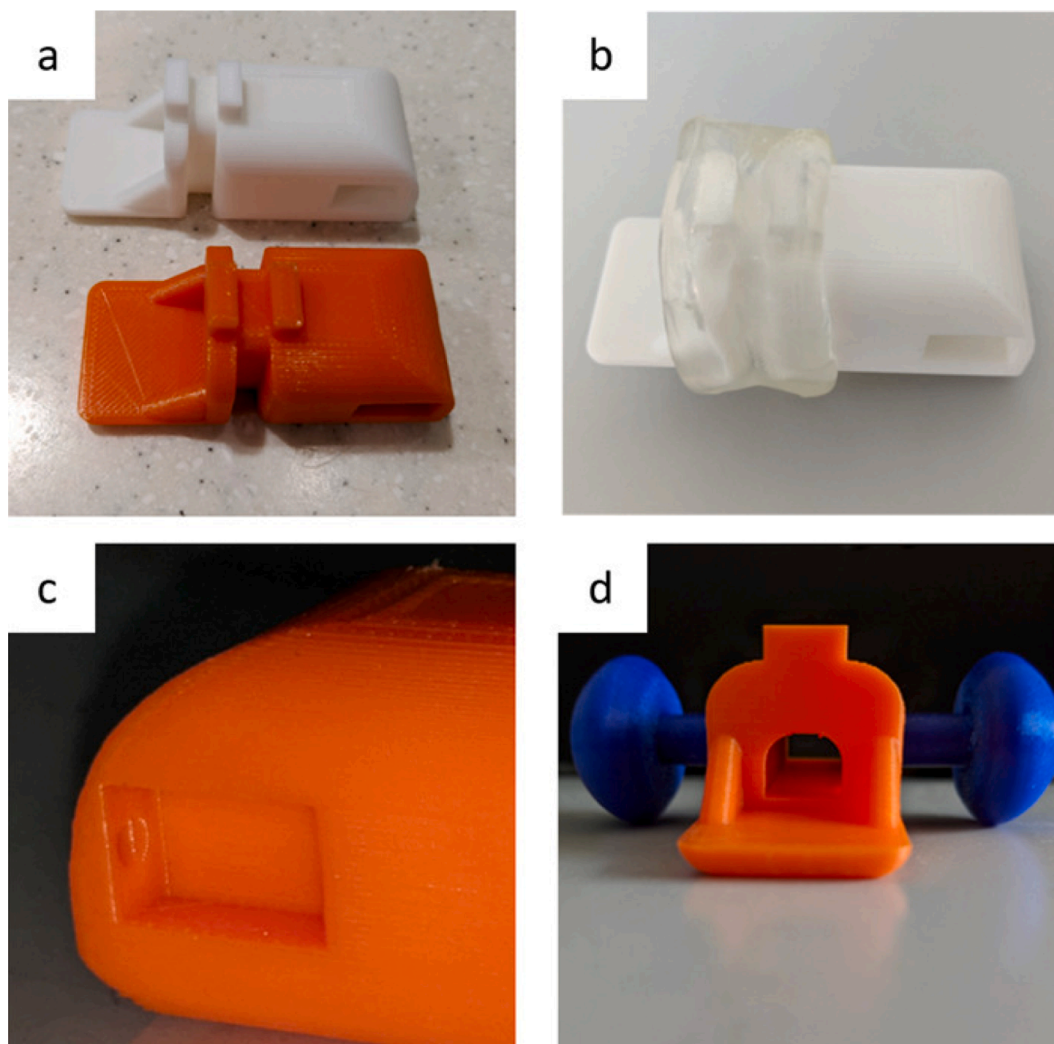The optional cheek displacement pieces were each designed with a

Fig. 1. Photographs of the intra-oral stent showing (a) the smaller (orange) and larger (white) main piece; (b) the larger main piece with silicone attached; (c) a connection slot for the cheek displacement piece; (d) the smaller main piece with both cheek displacement pieces attached.

rounded stem to sit over the molars or premolars and an elliptical mushroom-like head to sit inside the cheek (Fig. 2(a)). Three different sizes of the cheek displacers (from 32 to 40 mm in length) were designed for patient-specific customisation, to allow cheek displacements of up to 20 mm, depending on the lateral position of the teeth and the specific clinical need (Fig. 2(a)).

3.2. Fabrication

The main piece was printed on the Raise3D Pro 2 printer using PLA, with an in-fill percentage of 30% and three outer shells, to ensure strength and durability while minimising beam perturbation and scatter. The availability of PLA in various colours allowed the differently sized main pieces to be colour coded - orange for use in smaller mouths and white for use in larger mouths (see Fig. 1(a)).

The cheek displacement pieces were printed on an Ultimaker 2 Extended+ printer using TPU. Printing each cheek displacement piece was challenging due to the prominent overhang between the head and the stem. To arrive at an even surface on the underside of the overhang, multiple support systems were tested, with the "tree" support system shown in Fig. 2(b) providing optimal results. Multiple infill patterns, percentages and gradients were evaluated for optimal strength and flexibility, with a 12% gyroid infill percentage ultimately selected for the top 2/3 of the head to generate a cushioning effect (see Fig. 2(c)).

The same infill percentage was used for the base of the stem to allow manual compression and expansion, to achieve a stable connection into the main piece. For strength and durability, a 30% infill percentage was set between the bottom 1/3 of the head and the middle of the stem. Considerable adjustments from standard Cura TPU print settings where required to optimise material flow while reducing filament leakage, including the use of retraction, reduced material flow and speed when printing the stem.

3.3. Imaging

Fig. 3(a)-(f) show representative sagittal slices (Fig. 3(a)–(c)) and coronal slices (Fig. 3(d)-(f)) though MRI images of the healthy volunteer without an oral stent (Fig. 3(a) and (d)) and with a 3D printed intra-oral stent that included either one cheek displacement piece (Fig. 3(b) and (e)) or two cheek displacement pieces (Fig. 3(c) and (f)). Comparison of Fig. 3(a) and (b)-(c) indicates the extent to which the main part of the 3D printed intra-oral stent successfully held the mouth open and depressed the tongue. Comparison of Fig. 3(d) and (e)-(f) indicates the extent to which the cheek displacement pieces successfully displaced one cheek (Fig. 3(e)) and two cheeks (Fig. 3(f)) away from their relaxed position alongside the teeth (Fig. 3(d)). These results are quantified in Table 1.

Table 1 lists the distances between oral landmarks, as measured using the MRI images. These results indicate that the main piece of the
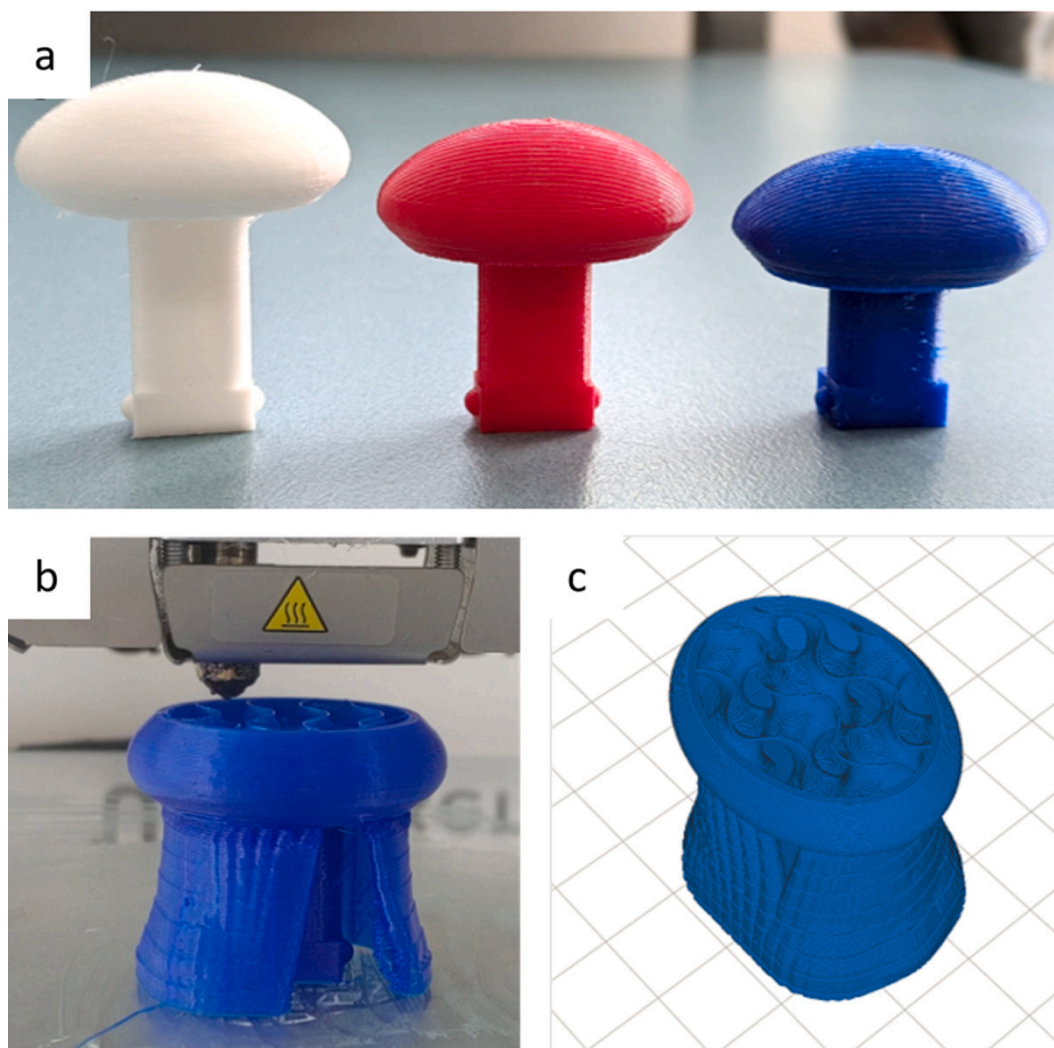
Fig. 2. The cheek displacement piece showing (a) the three different sizes of cheek displacement pieces (b) during printing and (b) design of gyroid infill pattern and the support structure around the stem.

3D printed intra-oral stent is able to depress at least a 20 mm length of the tongue, while keeping the mouth open (measured at between visible soft tissue on the mandible and maxilla sides of the mouth in sagittal slices) by more than 25 mm. Comparison of cheek-to-cheek distances in Table 1 (measured between left and right inner cheek walls visible in coronal slices) indicates that each of the medium cheek displacement pieces has displaced the cheek more than 12 mm from its relaxed position.

The participant experienced no additional discomfort or stress due to the stents during MRI imaging and reported surprise that the stents, which appeared large and ungainly upon visual inspection, were "quite comfortable".

3.4. Cleaning

Brief washing and rinsing of the assembled three-piece intra-oral stent resulted in a weight increase of nearly 0.2 g, from 23.09 ± 0.03 g to 23.27 ± 0.02 g after manual drying. Soaking the stent in a cleaning solution for 24 h resulted in a weight increase of more than 0.7 g, to 23.8 ± 0.4, after manual drying. Regardless of cleaning duration, the stent returned to its dry weight, measured at 23.10 ± 0.05, after an additional 60 s of blow drying. These measurements indicated that no plastic was lost from the stent and no cleaning solution was permanently absorbed during cleaning.

3.5. Costs

The two 3D printers used in this study cost approximately €2000 and €5000 to purchase and ship to Australia in 2018–2019. Although 3D printers capable of fabricating all these stent pieces can now be purchased for under €1000 [12,24], the upfront cost of printing hardware remains substantial compared to the low cost of printing materials. All software used in this study was either freely available (Cura, ideaMaker) or replaceable with freely available alternatives (AutoCAD).

The material cost of each stent piece, shown in Table 2, were comparatively low, with no combination exceeding €3.25 (at time of study). All the TPU cheek displacement pieces were more costly in terms of both time and money than the PLA main pieces, due to the increased cost of TPU filament compared to PLA filament as well as the increased internal complexity and external support structures needed by the TPU prints (see Fig. 2(b)-(c)).

The time cost of completing all the initial design, consultation, refinement and test printing involved in devising the final stent models was not tracked, but can be assumed to have amounted to many days work involving multiple individuals. With access to the final set of designs, the time cost of starting each print and confirming the correct operation of the printer during the first few layers, was no more than 15 min per piece.
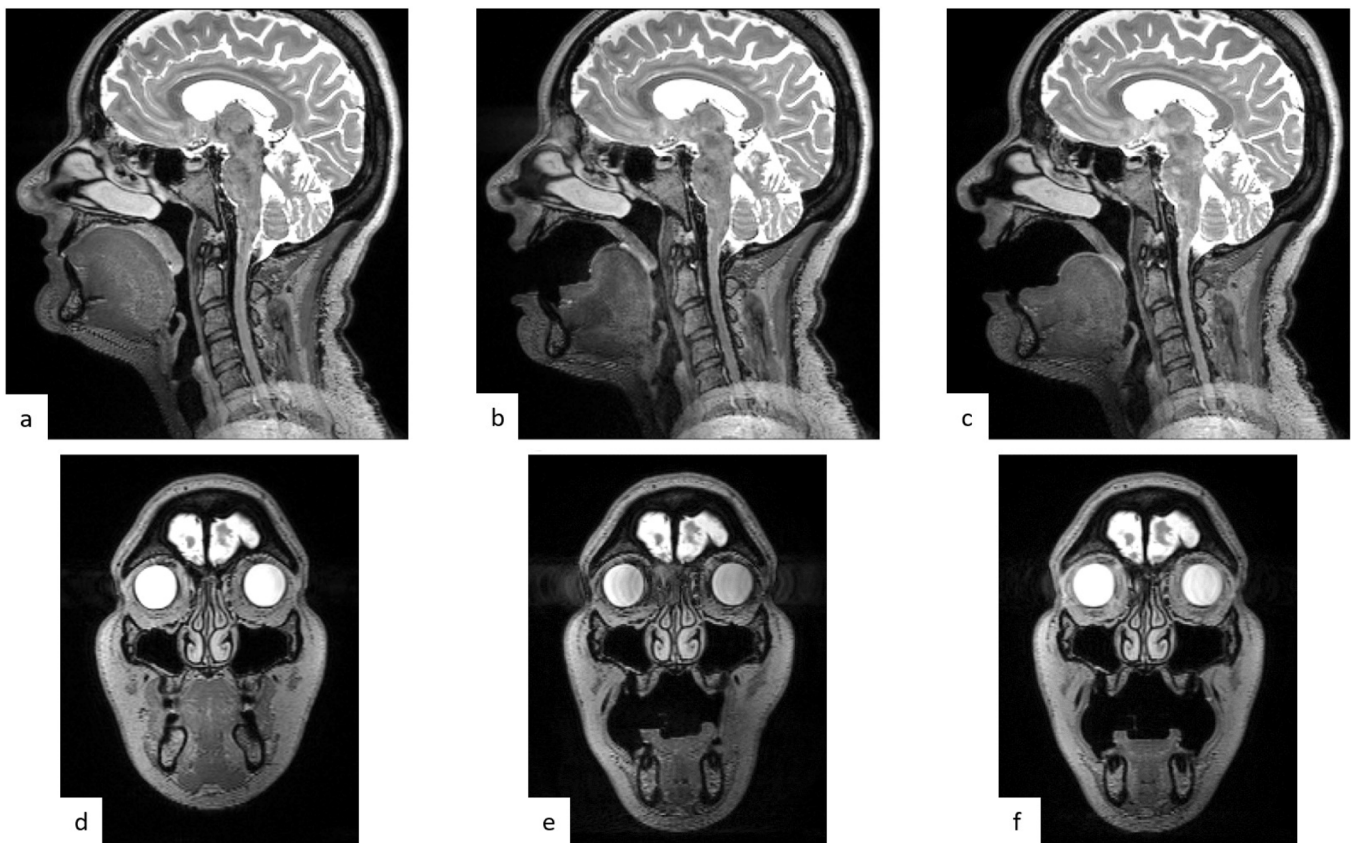
Fig. 3. Sagittal slices through MRI images with (a) no stent, (b) 3D printed stent with one cheek displacement piece, (c) 3D printed stent with two cheek displacement pieces, and coronal slices through MRI images with (d) no stent, (e) 3D printed stent with one cheek displacement piece, (f) 3D printed stent with two cheek displacement pieces.

Table 1
Distances between anatomical landmarks as measured on repeated MRI images of participant with and without different 3D printed stent options, where "one cheek" denotes the use of one cheek displacement piece and "two cheek" denotes the use of two cheek displacement pieces. (All measurements are in mm.)

Feature	No stent	3D print, one cheek	3D print, two cheek
Length of tongue depressed	N/A	20 ± 1	22 ± 1
Max. distance tongue to palate	N/A	35.7 ± 0.7	37.4 ± 0.3
Mouth opening height	N/A	27.3 ± 0.5	27.2 ± 0.7
Max. distance cheek-to-cheek	53 ± 3	65.9 ± 0.7	78.0 ± 0.3

Table 2
Print time and monetary cost of each piece of the 3D printed intra-oral stent.

Piece	Print Time (min)	Cost (€)
PLA small main piece	109	0.28
PLA large main piece	123	0.33
TPU small cheek displacer	113	0.73
TPU medium cheek displacer	118	0.77
TPU large cheek displacer	126	0.82
silicone Sheet	N/A	0.31

4. Discussion

This study designed and investigated a 3D printed stent for stabilising and displacing non-involved tissues in the oral region, to assist in reducing radiation side effects from radiotherapy treatments of head-and-neck cancer. While 3D printing can take 2 h or more for each stent piece (see Table 2), the modular design of this intra-oral stent would allow all pieces to be printed prior to the CT imaging session while the customisable options would still allow the stent to fulfill a range of displacement and immobilisation objectives.

Customisation was made possible by including different sized ready-to-use pieces that could be connected to achieve the desired level of tongue, jaw and cheek displacement, as shown in Fig. 4. The main piece could be used on its own to provide a tongue depressing, jaw opening effect. Alternatively, one cheek displacement piece could be added to displace either the left or right cheek away from the radiation beam (see Fig. 3(e)), or two cheek displacement pieces could be added to displace both cheeks (see Fig. 3(f)). If substantial adjustments were required for an unusual patient case, a new piece could be printed within a few hours.

Once the stent is assembled, a small piece of silicone can be wrapped around the grooves in the main piece, to allow teeth impressions to be taken, to achieve patient-specific positional reproducibility. For patients with no teeth, additional silicone can be built up on the anterior side, to ensure the stent stays in place when the patient is lying supine for imaging or treatment.

MRI imaging showed that the 3D printed intra-oral stent was able to achieve a similar degree of mouth opening and tongue depression as dentist-designed stents [5,7] or generic wedges [17], while demonstrating cheek displacements previously only reported in a phantom study using a wax stent and a 3D printed replica [12].

While quality assurance of 3D printed devices used in radiotherapy has been the focus of several recent publications [25–27], recommended tests of the geometry and density were not performed for the 3D printed pieces of the intra-oral stent. This study limitation was accepted in this work due to the comparatively low in-fill densities of the prints, the use of MRI imaging to evaluate print effectiveness and the final intention
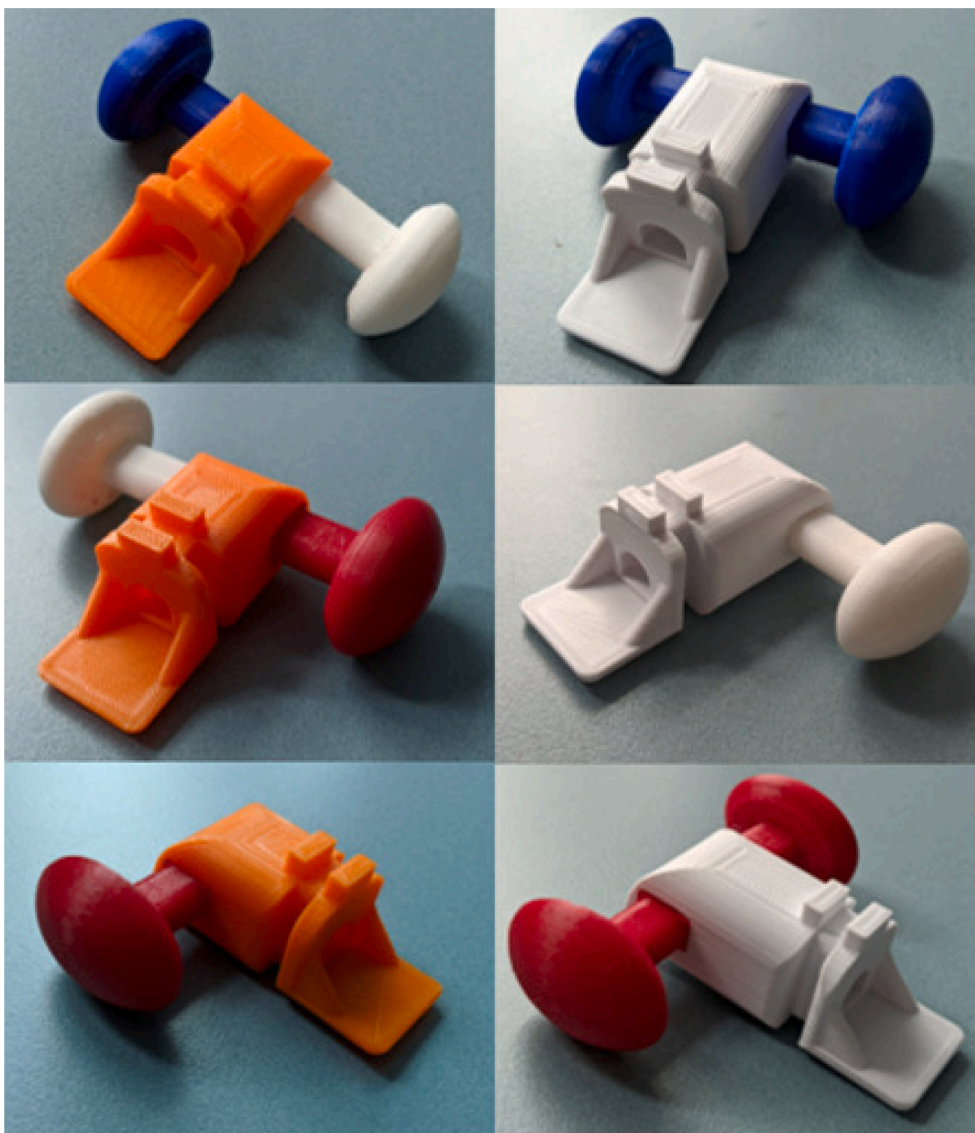
Fig. 4. Photographs of the 3D printed intra-oral stent, showing example arrangements of small and large main pieces with and without small, medium and large cheek displacement pieces.

that the stents would be printed in advance of patient CT imaging and would therefore be included in all planning CTs, so that any issues with print distortion or density variation would be accounted for in the radiotherapy treatment plan and dose calculation.

For safe clinical implementation of intra-oral stents, biocompatible materials are required to comply with international standards [28]. However, the biocompatibility of the finished product is dependent on a number of factors including biocompatibility of the material itself, biocompatibility of the printing process and the ability to clean sufficiently to comply with infection control requirements [29]. During printing, brass nozzles have been shown to leach lead into 3D prints [30], so use of a dedicated stainless-steel nozzle is therefore recommended for clinical use. The heat distortion temperatures of PLA and TPU are low enough to prevent the use of autoclave sterilisation [31]. Instead, depending on the regulatory environment, washing and soaking the printed pieces in a cleaning solution may be an acceptable method for cleaning if local regulations allow, given that the 3D printed stent pieces developed in this work were shown to be unaffected by washing and soaking when blow-drying is used to ensure no liquid adheres to the plastic.

Safe clinical use of this customisable stent should also involve the use

of rigid external fixation via a thermoplastic mask, such as should be used for any modulated head-and-neck radiotherapy treatment [32]. A hole can be cut in the mask to accommodate and easily remove the stent, and the mask should ideally have easy-release clips so that the patient can be speedily released if they begin to feel uncomfortable or unwell during treatment. Accurate positioning of the mouthpiece and all relevant anatomy should be verified via pre-treatment imaging methods, such as cone-beam computed tomography, since positioning errors are well known to detrimentally affect target coverage and increase the risk of toxicities from modulated, conformal head-and-neck radiotherapy treatments [33,34].

Previously Zhang et al. [35] and Doi et al. [4] have used pre-treatment images of head-and-neck radiotherapy patients to evaluate patient positioning reproducibility during head-and-neck radiotherapy treatments, respectively showing that the use of oral stents could reduce positioning errors in the superior-inferior and anterior-posterior directions. By contrast, the current study was limited by reliance on MRI imaging of one healthy participant, rather than investigating positioning effects for multiple head-and-neck cancer patients. While working with a healthy, compliant and communicative volunteer allowed a challenging series of repeated MRI images to be completed efficiently, with

clear verbal evaluations of each stent provided between scans, the comfort and reproducibility results reported in Section 3.3 should be regarded as best-case indications of achievable performance. Similarly, while the anatomical displacement measurements reported in Section 3.3 were largely determined by the stent shapes, the irregular oral anatomy of head-and-neck cancer patients may also result in different and unexpected distortions. Nonetheless, the results of this study and the positive response of the participant demonstrate the potential for customisable modular intra-oral stents to benefit future head-and-neck radiotherapy patients.

5. Conclusion

Utilising 3D-printing technology, a novel intra-oral stent design was developed for use in head-and-neck radiotherapy. The design incorporated a main piece with an integrated jaw opener and tongue depressor, the ability to integrate patient-specific teeth impressions, and optional cheek displacement pieces. The results of testing the stent with a healthy and compliant volunteer suggest that the modular and customisable stent design provides the ability to achieve a range of stable oral displacements without the workflow interruption associated with 3D printing time. Routine use of these pre-fabricated stents has the potential to reduce toxicities related to head-and-neck radiotherapy treatment.

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.

Acknowledgements

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