# 3D-printed surface mould applicator for high-dose-rate brachytherapy

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**ABSTRACT**

PURPOSE: In contemporary high-dose-rate brachytherapy treatment of superficial tumors, catheters are placed in a wax mould. The creation of current wax models is a difficult and time consuming proces.The irradiation plan can only be computed post-construction and requires a second CT scan. In case no satisfactory dose plan can be created, the mould is discarded and the process is repeated. The objective of this work was to develop an automated method to replace suboptimal wax moulding. METHODS: We developed a method to design and manufacture moulds that guarantee to yield satisfactory dosimetry. A 3D-printed mould with channels for the catheters designed from the patient's CT and mounted on a patient-specific thermoplastic mesh mask. The mould planner was implemented as an open-source module in the 3D Slicer platform. RESULTS: Series of test moulds were created to accommodate standard brachytherapy catheters of 1.70mm diameter. A calibration object was used to conclude that tunnels with a diameter of 2.25mm, minimum 12mm radius of curvature, and 1.0mm open channel gave the best fit for this printer/catheter combination. Moulds were created from the CT scan of thermoplastic mesh masks of actual patients. The patient-specific moulds have been visually verified to fit on the thermoplastic meshes. CONCLUSION: The masks were visually shown to fit onto the thermoplastic meshes, next the resulting dosimetry will have to be compared with treatment plans and dosimetry achieved with conventional wax moulds in order to validate our 3D printed moulds.

## PURPOSE

In high-dose-rate (HDR) brachytherapy radioactive sources are temporarily brought to the target tissue via catheters. For superficial lesions, the catheters are incorporated in a surface mould in a non-invasive manner (Figure 1). In contemporary practice, a technician creates a thermoplastic mesh of the patient's body surface in the region of interest. The thermoplastic mesh helps to restrict the patient's movement during treatment. The mask is removed from the patient and surface mould is then created on top of the thermoplastic mesh. Catheters are fixed in the mould using wax pieces about 3-5mm from the surface of the skin. If the surface is flat then catheters can run parallel else if the area is more complex than the paths require a more ad-hoc pattern. The catheter placements should be evenly distributed of over the region of interest so that the radioactive sources can deliver radiation to all cancerous tissue. The purpose of the wax surface mould is to restrict movement of the catheters during the entirety of the treatment process.

**Fig. 1.** Conventional wax surface mould on a thermoplastic mask

After the catheters are secured within their wax mould the patient is once again placed back into the thermoplastic mesh. Dummy sources (radio-opaque wires) are pushed into all catheters and a CT image of the patient in the mask is sent into a treatment planning software that computes the optimal irradiation plan for the catheters embedded in the mould. The treatment plan is analysed by a radiologist and if planning reveals poor path placement, or an incorrect dose distribution the mask is discarded and a new one is constructed from scratch. Once a suitable plan has been constructed the treatment is typically delivered in 10 fractions (2x a day for a week).

Crafting a conventional wax mould is a time consuming manual enterprise. The placement of catheters is an intuitive and subjective process based on practice and experience, yielding a mould that is unchangeable once the wax sets. The dose planning software can only be run after the channels are embedded into the wax mould and rescanned in CT. The goal of this project is to create a module in the open source medical imaging program 3D Slicer[1] that creates such a custom applicator. Using this module a mould of the area to be irradiated is created based on a CT scan of the patient, this mould can be built on top on either the skin surface or a thermoplastic mesh. Catheter paths can out of the mask based on optimized radiation treatment paths defined by a medical professional. The resulting mask is then exported in a format that can be used by a 3D printer. The use of a completely customized applicator for each patient allows for careful optimization to be done on the radiation dose planning, such as placing the catheters an optimal distance from the area to be irradiated so that the radiation does not penetrate too deeply and harm healthy tissue. Due to the increasing popularity of 3D printing and other such technologies it is now feasible to create customized applicators for every patient.

## NEW OR BREAKTHROUGH WORK TO BE PRESENTED

We developed a method to semi-automatically generate a 3D-printed rigid mould from a CT scan of the patient wearing the thermoplastic radiotherapy mask, yielding a mould that fits correctly on the mask. An augmented CT volume of the catheter paths can be used to dose planning prior to printing, if the achieved treatment plan is not satisfactory the mould can be redesigned. High quality plans can be printed ready for dose delivery.

## METHODS

To calibrate the 3D printer for the dimensions of a catheter a calibration object was needed (Figure 2). Printing may cause features to be consistently larger or smaller. While threading the catheters through the mold, friction between the printed material and catheter may require the mould's channel diameter and minimum radius of curvature to be larger than the catheter's manufactured specifications. A slit is running along the path are also added to the object. The slit has three functions, it ensures the 3D printing support material is completely dissolved from the channels, faster dissolving of support material, and allows the mould to fix the catheters in place with the addition of glue. The calibration object has been designed to allow users to create slots that vary in radius, maximum curvature, and slit dimensions. When a catheter can pass through

**Fig. 2.** Calibration object to determine optimal channel dimensions

a slot with a tight fit, the dimensions of that slot determine the numerical inputs for the mould building module for the given printer-catheter combination.

A CT scan of the patient wearing the thermoplastic radiotherapy mask is acquired (Figure 1). The scan in DICOM format is loaded into 3D Slicer[1]. The volume is cropped with a region of interest box then run with a windowed Sinc interpolator[2] at a scaling constant of 0.5mm. The volume is binarized then dilated/eroded to remove small holes and noise in the thermoplastic mesh. The volume can optionally be smoothed with a Taubin smoothing filter[3]. The modified volume is then converted into a model using the marching cube algorithm[4]. This model is then sent to a a mould building module to help define the shape and size of the surface mould.

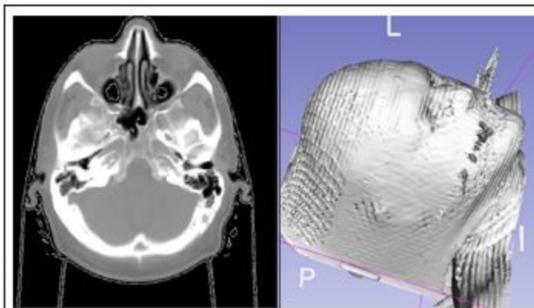



**Fig. 3.** The CT Scan (left) and the 3D mask mesh model(right) constructed from the thermoplastic seen in Figure 1.

The mould building workflow (Figure 4):

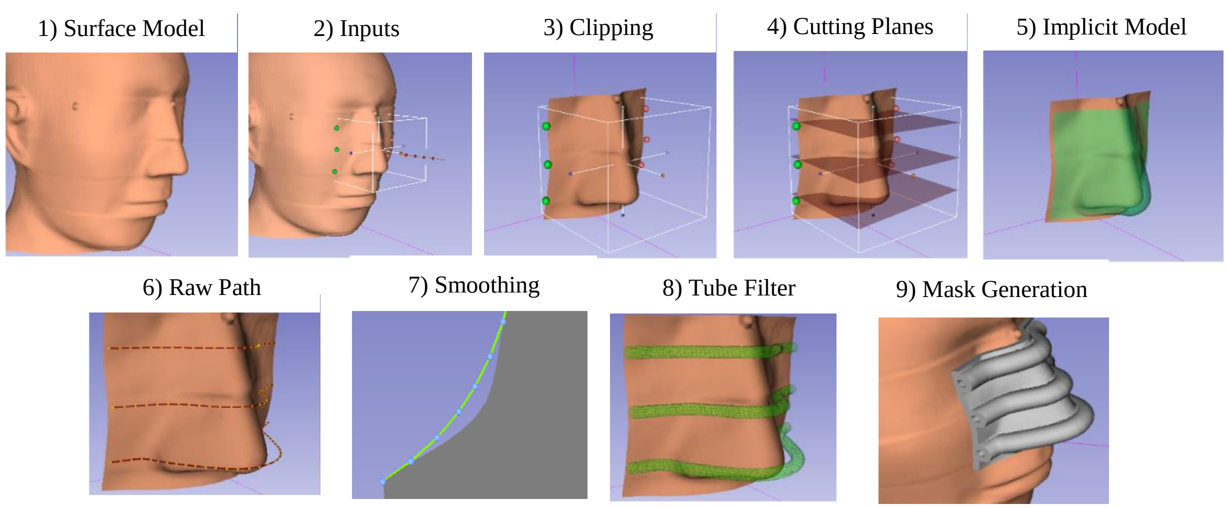
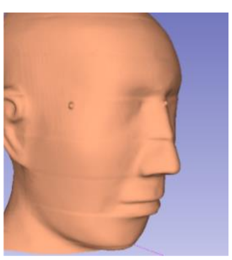
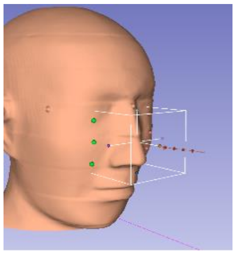



**Fig. 4.** Workflow in the surface mould builder module in 3D Slicer

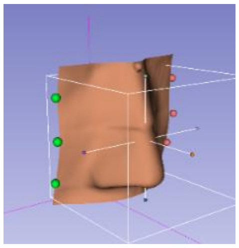
**1)**



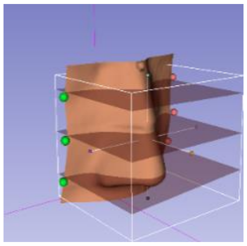
**Surface Mould:** The largest region is extracted from the smoothed input model with a connectivity filter which extracts only regions connected to the outer surface. This removes artifacts inside the surface. We may choose to use either the patients skin surface or the thermoplastic mesh surface as the surface in which to build the mould on.

2) 

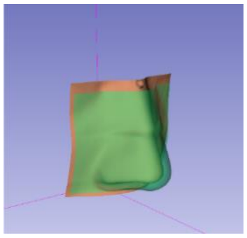
**Inputs**: The module requires a 3 object inputs: A region of interest box to be defined around the area in which the mould is to be created (white box). Placements of start (green spheres) and end points (red spheres) define the path of the catheters. A ruler object (red line) is used to allow definition of the front of the mask and orientation of the paths. The numerical inputs from a calibration object define the channel radius, curvature and slit dimensions.

3) 

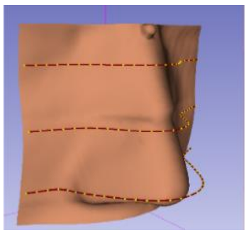
**Clipping:** A implicit boolean clips the portion of the surface within the extents of the ROI. This gives us the localized surface to work with for the rest of the algorithm. This surface also plays a crucial role in the mould creation step in which we use this clipped surface to subtract away artifacts from the channel generation yielding a mould that fits correctly onto the patient's skin or thermoplastic mesh surface.

4) 

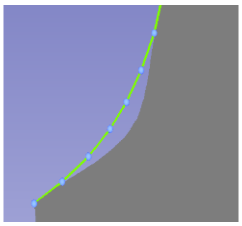
**Cutting Planes:** For each catheter path, an implicit plane is created using the ruler's vector and the start and end point of the path. This cutting plane represents the path from start to end points , along which the path will move.

5) 

**Implicit Model:** The clipped surface expanded outwards by the minimum aloud distance of a catheter (vtkImplitModeller). This mask (green surface) specifies the closest allowed distance a catheter can be from the original surface. Using this cutting planes and this implicit model mask we can generate a set of point running from the input start and end points that is guaranteed to be greater than the aloud distance of the catheter. Normally, this value is about 15mm which is derived from the minimum thickness required by the 3D printing material.

6) 

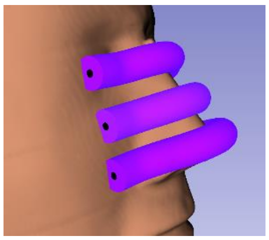
**Raw Path:** With the cutting plane we slice the minimum distance mask which produces a raw path (red lines) exactly at the minimum allowed distance from the face. This path may still be in violation of the minimum allowed curvature specified by the catheter manufacturers (10mm), so further processing is required to smooth the paths, while maintaining the minimum thickness constraint.

7) 

**Smoothing:** The raw path is smoothed with a filter. In order to decrease curvature without violating the minimum distance requirement, two movements are required. Convex points are pushed in the direction of the circumcenter. Concave points remain stationary and push adjacent points in the inverse direction of its own circumcenter. After each movement a check is preformed to avoid a situation where self-intersection occurs.

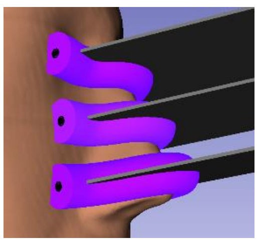
**8)** 

**Tube Filter:** Multiple tube meshes are created from the smoothed path with a tube filter. The tube meshes represent the hollowed area existing within the 3D printout for which the catheters will run through. The polygon meshes are stored for future mask generation steps.

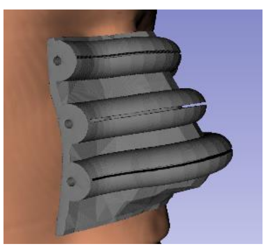
**9)** 

**Mask Generation:** To create a surface mould. The objects are converted into binarized images to allow for quick additions and subtractions during the creation of the mask.

First channels are created with a radius 1.5mm + the optimal catheter radius found from the calibration step. This is to ensure the structural integrity of the 3D printed material. The tubes from step 8 are then subtracted from the channels to create paths for the catheters to run through.



During early iterations, printouts required long bathing times to remove inner printout material from within the tube. It was found that slits reduced the bathing times for clearing out the material within the mould. Slits are created for each path and then removed from the outter face of the mask.



The clipped surface from step 3 is bubbled out to create a base in which all the tubes will be held in. This entire object is now subtracted using the skin surface /thermoplastic mesh  in order to fit onto the patient. The model is then converted into an STL format and set to the 3D printer to print.

## RESULTS

A calibration object, shown in Figure 2, was printed using the Dimension sst 1200es. The calibration slots contained 3 different radii: 1.0mm , 1.33mm and 1.66mm. A slit width of 1.0mm were used for 1.0mm and 1.3mm paths and a slit of 1.5mm for 1.66mm paths. Each radii was tested at 4 minimum radius of curvatures: 10mm,12mm,14mm,16mm. The catheter fit the slot 1.33mm radius and radius of curvature with 12mm. The calibration will be used for any further models containing 1.7mm G.B Tech Tube printed with the Dimension sst 1200es. Three medically constructed thermoplastic meshes with complementary CT scans have been given to our project from Kingston General Hospital.  3D surface models were successful built using the HDR brachytherapy surface mould creation algorithm on the thermoplastic meshes (Figure 5). Areas around the mouth caused complications for surface mould building due to artifacts from the CT scans caused by a patient's dental work. The models constructed in the 3D slicer where printed with Dimension sst 1200es. An adhesive can be simply applied to the bottom to stick the mould onto the mask for clinical situations.

**Fig. 5.** Left: Thermoplastic mesh received from Kingston General Hospital. Middle: recreation of surface in 3D slicer. Right: Instantiation of a surface mould

The masks were visually verified to be well fitted to the meshes (Figure 6).

**Fig. 6.** The mould was found to fit correctly on the thermoplastic mesh without visual inconsistencies

## CONCLUSIONS

The proposed 3D-printed patient mould are objectively designed and built from a computer model and thus are expected to outperform manual wax masks, in terms of both dosimetric accuracy and consistency. Moreover, the design and production of a 3D-printed mould needs only a small fraction of technologist's time, compared to building manual wax masks. The existing three patient-specific moulds were found to all fit correctly onto their thermoplastic meshes. The resulting treatment plan and dosimetry will be compared with treatment plans and dosimetry generated from conventional wax moulds.

## ACKNOWLEDGEMENTS

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