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Personalized phantoms through 3D printing

Introduction to 3D printing

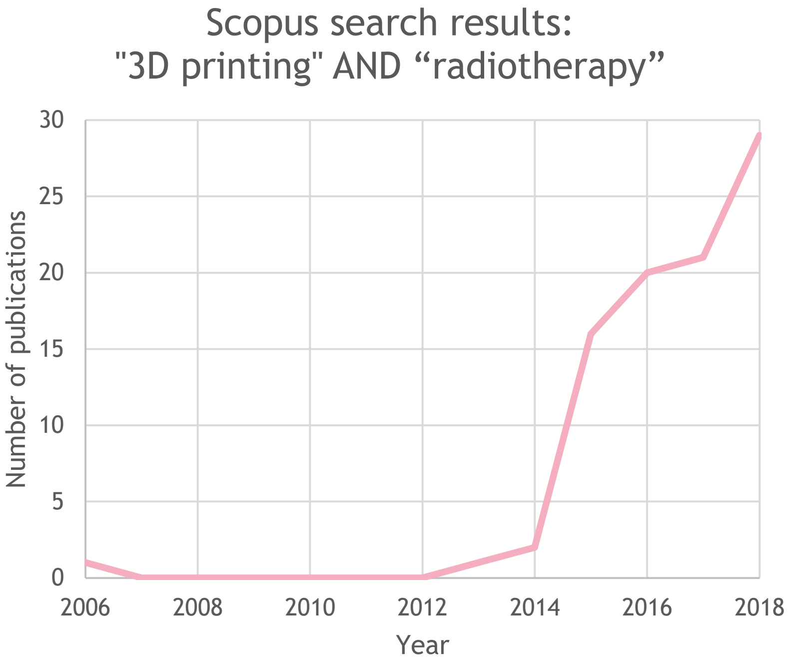
- 3D printing, or more broadly additive manufacturing, allows the fabrication of 3D objects in various materials, including plastics and metals.

- 3D printing has been around for a while, but affordable systems have become broadly accessible in the past 5-10 years. Anecdotally, about 50% of Australian radiation oncology centres either have 3D printers on site, or are outsourcing the 3D printing of equipment such as bolus and superficial applicators.

- There are various technologies / processes, including:
  - Deposition of an extruded filament material (e.g. fused deposition modelling). [See Adaptiiv display in exhibitor area].
  - Photo-polymerisation of a resin (e.g. stereolithography).
  - Binding, melting or sintering of a powder material (e.g. laser sintering).

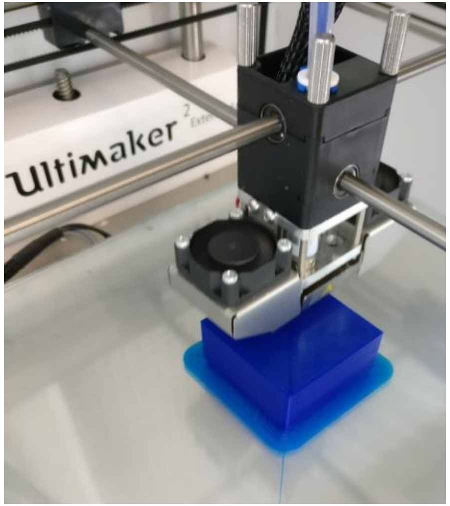
3D printing in radiation oncology

- 3D printing has been rapidly adopted for various medical applications, e.g. surgical planning.
- Gradually being adopted in radiotherapy. Treatment equipment includes:
  - External beam treatment modifiers, e.g. bolus[1], compensators[2], cut-outs[3].
  - Fixation/positioning equipment, e.g. masks[4] and mouthpieces[5].
  - Superficial brachytherapy[1] and intraoperative radiotherapy[6] applicators, and needle templates[7].



3D printing of radiotherapy phantoms

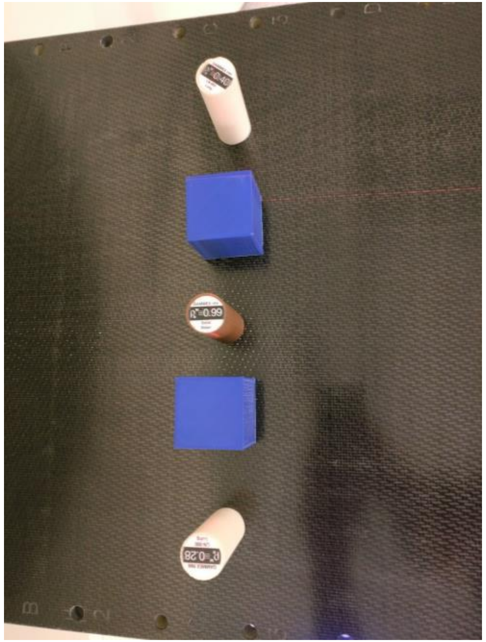
- For a medical physicist, 3D printing allows the fabrication of a wide variety of tools for quality assurance, of varying complexity:
  - dosimetry equipment such as jigs or build-up caps;
  - simple phantoms for mechanical, dosimetric and imaging QA;
  - custom inserts for existing QA phantoms;
  - anthropomorphic phantoms;
  - phantoms with variable densities;
  - phantoms with deformable or movable parts
  - embedded radionuclides or dosimeters
- I'll present some examples from my department.



Within our department we have an Ultimaker 2 Extended+ (FDM) and Form1+ (SLA); and some staff also have their own systems (e.g. an Aldi-purchased wanhou i3)

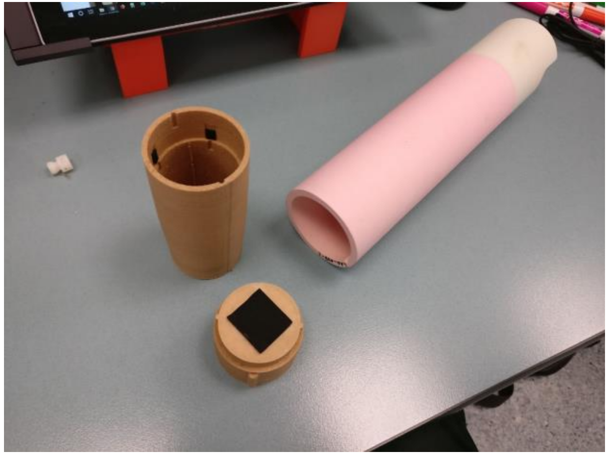
3D printing phantoms: simplest cases

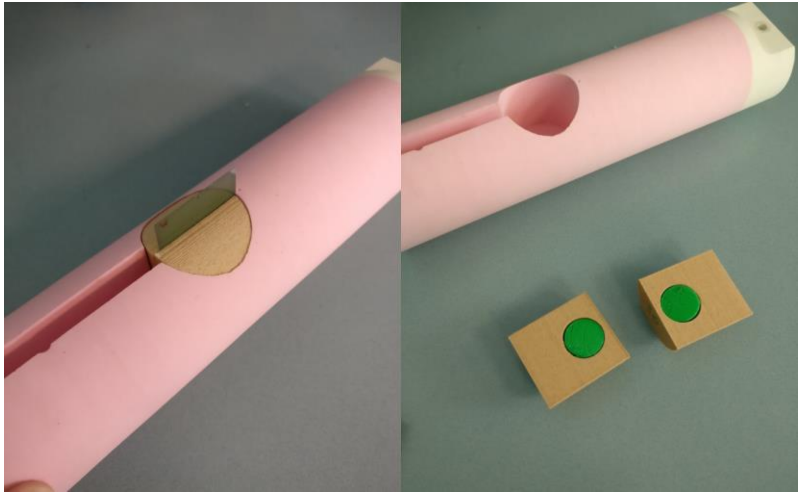
- Simple prints we've done in our department include:
  - Sleeves for (non-Farmer) ionisation chambers to fit within ^{90}Sr check source.
  - Attachments for specific detectors in the the water tank.
  - Stackable cubes with lung and tissue densities, for constructing simple phantoms.
  - Simple phantoms for holding dosimeters.



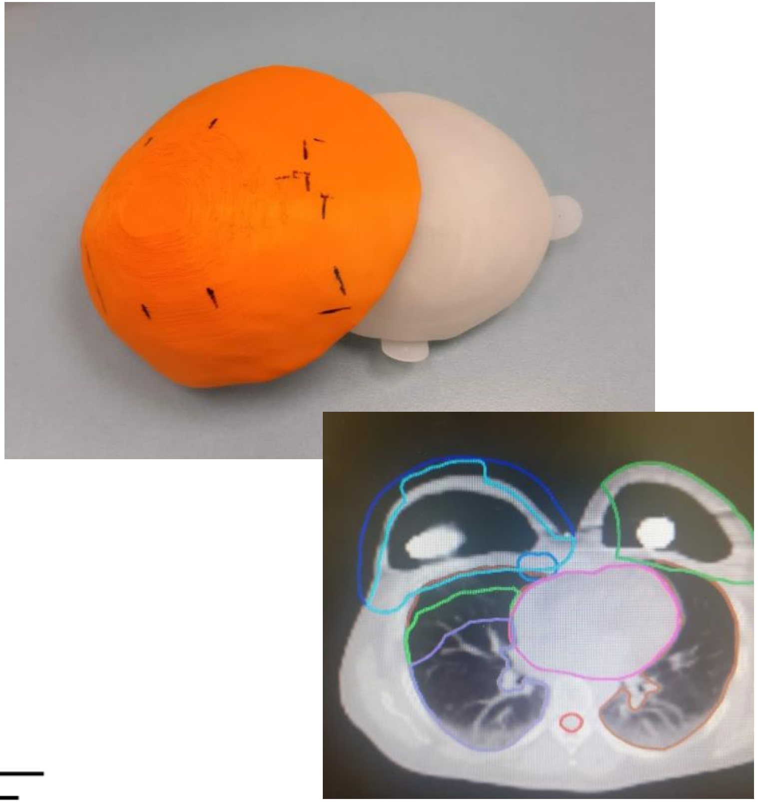
3D printing phantoms: inserts for existing phantoms

- 3D printing allows fabrication of custom inserts for existing QA phantoms. Shown: lung tumour inserts for film and gel measurements for CIRS Dynamic Thorax Phantom 008A. PLA wood fibre composite used for lung.





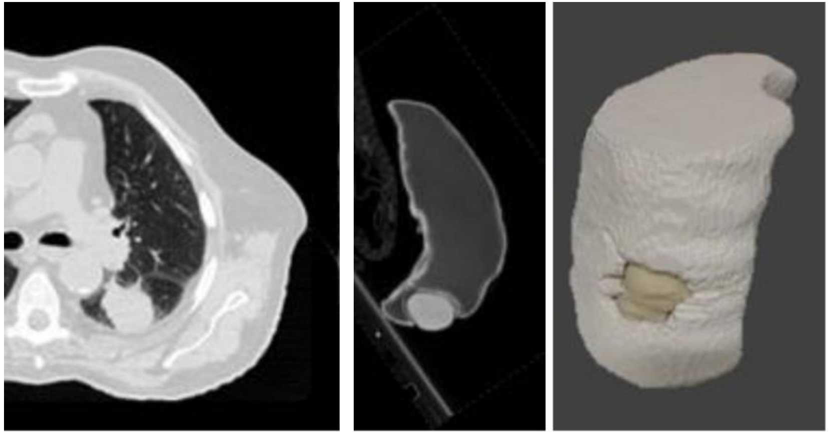
3D printing phantoms: anthropomorphic phantoms



- Breast tissue phantom for placement on AirXpander AeroForm temporary tissue expander; to evaluate dosimetric impact of metallic CO_2 canister.

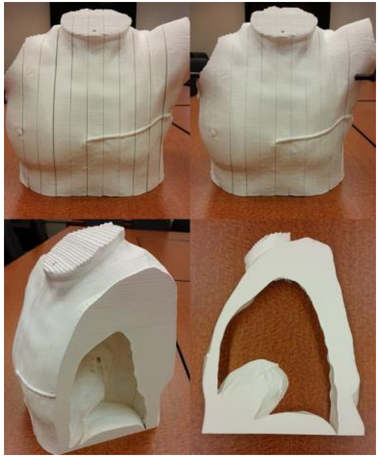
3D printing phantoms: anthropomorphic phantoms

- Larger volumes are possible – see lung with tumour. But for these large volumes, the use of wax or water filling for tissue may be preferable, to the cost (both $ and time) of 3D printing the tissue-equivalent media.
  - Craft & Howell[9] reported 267.5 h, $524 USD for 12 slice, 12.5 kg thorax



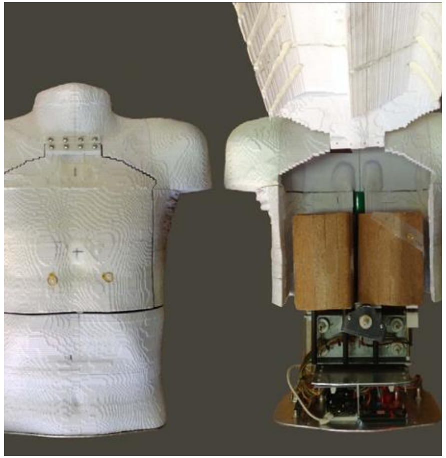
Kairn et al.[20]

Examples of what others have done

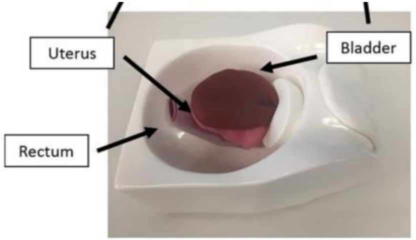


Craft & Howell[9]

Liao et al.[10]



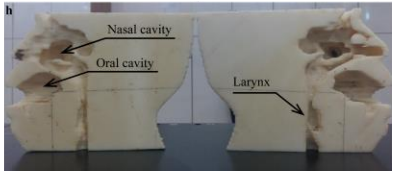
Palotta et al.[11]



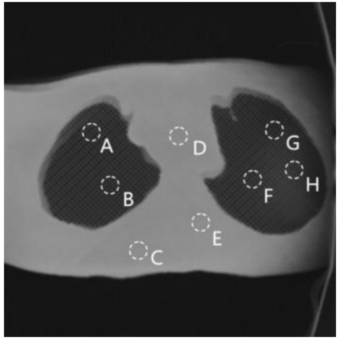
Kadoya et al.[12]

Oh et al.[13]

Hazelaar et al.[14]



Yea et al.[15]



Okkalidis[16]

Applications for 3D printed anthropormophic phantoms

- These phantoms are already being used for various clinical and research tasks.

- One benefit of 3D printed anthropomorphic phantoms is allowing clinically realistic end-to-end tests (also known as Level III audits). This could be done for:
  - Compliance with regulatory requirements. Within my departments region, treatment units must be independently audited with an end-to-end test; and this extends to modalities that are not so well serviced by commercial phantoms, such as brachytherapy.
  - Accreditation of departments for participation in clinical trials. With appropriate contrasts, the trial organisers could assess delineation, planning and delivery.
  - Education and training. There may be benefit for students to proceed through all steps of the treatment chain with a phantom designed for that process: simulation, planning, set-up, image-guidance, and treatment with verification by measurements.

How to do this in your department?

- Consider whether you need a 3D printer for your department, or if it makes more sense to outsource fabrication, particularly if you want materials other than ABS/PLA/TPU. Suppliers may provide web front ends providing quotes for uploaded STL files.

- Consider the following when deciding on a printer:
  - An enclosed print area can minimise warping effects.
  - Print bed should be able to be heated, and for large anthropomorphic prints, larger than usual.
  - Dual nozzles allow the use of a soluble material for printing supports.
  - Support for generic filaments preferable; and consider support for Nylon or high temperature filaments (PEEK) if you anticipate printing materials that can be autoclaved.

- Purchase spare nozzles and tools to clean up prints (e.g. dremel, side cutters, deburring tool).

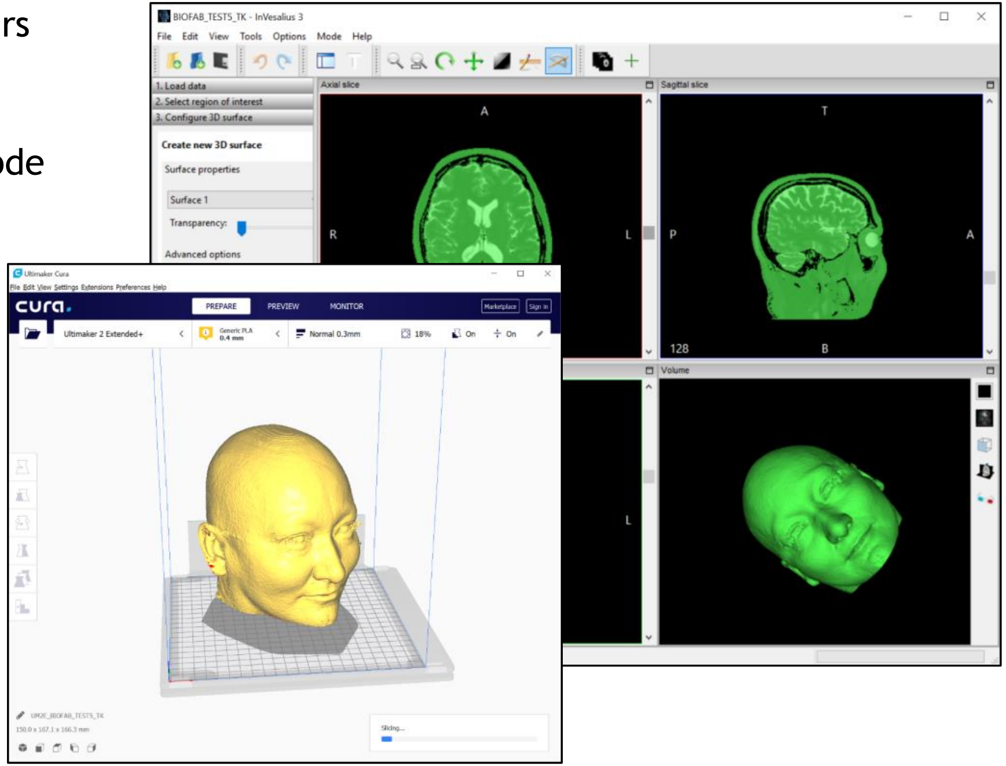
How to do this in your department?

- General models can be developed in free software such as Meshmixer, TinkerCad, Blender or SketchUp.
- For geometries requiring high precision (e.g. chamber cavities with minimal air gaps, or brachy catheter channels), you may need to experiment with tolerances.
- Radiological properties of materials have been described by various authors[16-18], by imaging or transmission measurements. These properties vary with filament used (not just e.g. ABS vs. PLA; but also with different batches of the same filament), printer and parameters, slicing application, in-fill patterns; so characterisation should be performed by users.
- For large volumes, you may have more success printing in pieces (e.g. 2 cm slices).

How to do this in your department?

- Models can be easily produced from contours on CT/MRI imagesets, e.g.:
  - Via treatment planning systems such as Varian Eclipse Scripting API Export3D code
  - Via complementary tools such as MIM Software Maestro STL export
  - Via independent tools using DICOM framework, such as InVesalius (invesalius.github.io) or 3D Slicer (www.slicer.org)

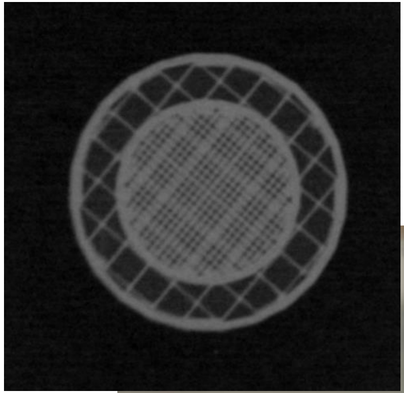
- Photogrammetry is another option.

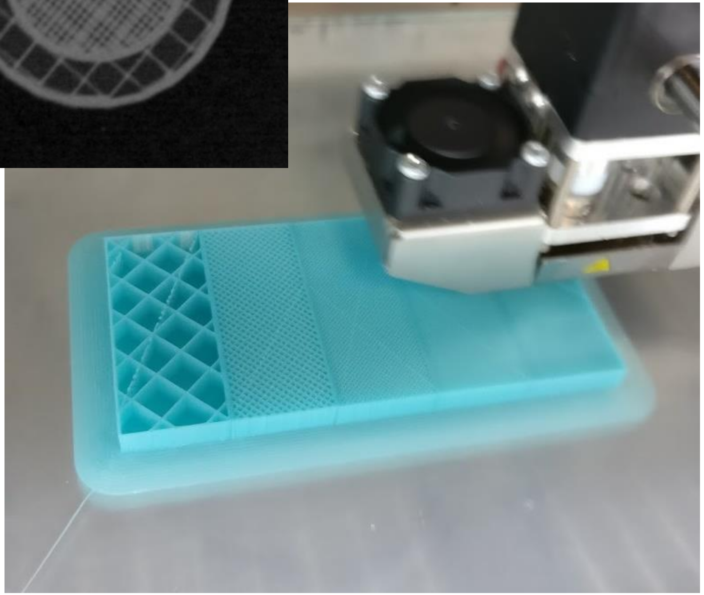


How to do this in your department?

- Variable densities can be achieved by printed components separately (with different in-fill densities and/or materials), the use of override models within slicing application (e.g. *modifier meshes* within Slic3r, *per model settings* within Cura), or the use of a pixel-by-pixel approach described by Okkalidis[16].

- For low in-fill densities, be mindful of potential variations in path length or scatter conditions with different in-fill patterns, particularly for small fields or high dose gradient sources (kV, brachy).





Conclusion

- We are reaching the point now where the literature in this space is not focussed on the development and fabrication of phantoms; but addressing research questions through the use of 3D printed phantoms.

- There was a 2018 Parallel-Opposed article by Ehler and Craft[19], discussing whether "3D printing technology will eventually eliminate the need of purchasing commercial phantoms for clinical medical physics QA procedures" (which I'd recommend reading). I don't think that will happen in the near future, particularly given variations in fabrication with different platforms, etc.

- But plenty of use cases already exist. I had heard it described, a few years ago, as a solution in search of a problem. I don't think that holds true. If you want to answer a particular research question; whether patient-specific or not; 3D printing could be the answer. And the cost of entry, in terms of money and experience (whether using in-house or outsourced printing), is low.

Acknowledgements & References

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