

Three-dimensional printing in congenital heart disease: Considerations on training and clinical implementation from a teaching session

Giovanni Biglino^{1,2}, Elena G Milano^{3,4}, Claudio Capelli^{3,5}, Jo Wray⁵, Andrew IU Shearn¹, Massimo Caputo^{1,6}, Chiara Bucciarelli-Ducci^{1,6}, Andrew M Taylor^{3,5} and Silvia Schievano^{3,5}

1 Bristol Heart Institute, Bristol Medical School, University of Bristol, Bristol, UK

2 National Heart and Lung Institute, Imperial College London, London, UK

3 Institute of Cardiovascular Science, University College London, London, UK

4 Department of Surgery, Dentistry, Paediatrics and Obstetrics/Gynaecology, University of Verona, Verona, Italy

5 Cardiorespiratory Division, Great Ormond Street Hospital for Children NHS Foundation Trust, London, UK

6 University Hospitals Bristol NHS Foundation Trust, Bristol, UK

Corresponding author:

Giovanni Biglino, Bristol Heart Institute, Bristol Medical School, University of Bristol, Bristol Royal Infirmary, Upper Maudlin Street, Bristol BS2 8HW, UK.

Email: g.biglino@bristol.ac.uk

Abstract

In light of growing interest for three-dimensional printing technology in the cardiovascular community, this study focused on exploring the possibilities of providing training for cardiovascular three-dimensional printing in the context of a relevant international congress and providing considerations on the delivery of such courses. As a second objective, the study sought to capture preferences in relation to three-dimensional printing uses and set-ups from those attending the training session. A survey was administered to $n = 30$ professionals involved or interested in three-dimensional printing cardiovascular models following a specialised teaching session. Survey results suggest the potential for split training sessions, with a broader introduction for those with no prior experience in three-dimensional printing followed by a more in-depth and hands-on session. All participants agreed on the potential of the technology in all its applications, particularly for aiding decision-making around complex surgical or interventional cases. When exploring setting up an in-house three-dimensional printing service, the majority of participants reported that their centre was already equipped with an in-house facility or expressed a desire that such a facility should be available, with a minority preferring consigning models to an external third party for printing.

Keywords Paediatric cardiac surgery, artificial kidney, apheresis & detoxification techniques, cardiac imaging, cardiac surgery, modelling cardiovascular, bioengineering

Introduction

Three-dimensional (3D) printing is increasingly recognised as a valuable tool in cardiac surgery and cardiology, and particularly in congenital heart disease (CHD), where the anatomical variability between patients and the complexity of surgical/interventional repairs warrants a patient-specific approach.^{1,2} The technology allows retaining patient-specific features through the manufacture of models that have been generated via image segmentation and volume rendering processing. These start from routinely acquired medical imaging data such as cardiovascular magnetic resonance (CMR) imaging or computed tomography (CT), and more recently also technologies such as 3D echocardiography and micro-CT.^{3,4} The availability of such CHD models opens the door to multiple applications, ranging from aiding the decision-making process for surgical/interventional planning to counselling families and communication with young people, and from medical education and training to designing experimental setups for researching specific CHD scenarios.⁵⁻¹¹ Multiple case studies, case series and a few randomised studies have begun to gather evidence with regards to these different applications and discuss the usefulness of 3D printing as a tool complementing multimodality imaging for complex CHD cases, as a means of engaging patients and enabling them to gain confidence about their condition or exploring their own narratives of illness or as guides for preoperatively planning tumour debulking in infants highlighting the spatial relationship between the tumours and coronary arteries.¹²⁻¹⁴ Alongside such growing interest in the clinical community and increasing recognition of the possibilities offered by 3D printing technology, methodological advances are rendering image-processing faster and, especially, the technology itself more accessible, with affordable desktop 3D printers able to produce models of very good quality for the applications outlined above. As a result of the growing interest in the CHD community and the increasing availability of the technology, new questions arise, including around standardisation of methodologies, training provision and possible configuration of 3D printing services. Guidelines for medical 3D printing and appropriateness for clinical scenarios are beginning to emerge,¹⁵ promoted by new dedicated special interest groups in relevant societies, such as the Radiological Society of North America (RSNA) 3D printing Special Interest Group (<https://www.rsna.org>) or the new Society for Cardiovascular Magnetic Resonance (SCMR) 3D + working group (<https://www.scmr.org>). Practical guides and primers are also appearing to

provide information and guide practitioners with an interest in cardiovascular 3D printing.¹⁶⁻¹⁸ In this light, we sought to explore further the possibilities of providing training for cardiovascular 3D printing in the context of a relevant international congress and provide considerations on the delivery of such courses. As a second objective for this study, we sought to capture preferences in relation to 3D printing uses and set-ups from those attending the training session.

Methods

Training session and participants

A 1.5 h long 3D printing training session titled 'From 2D images to 3D models' was organised in the context of the 2018 EuroCMR/SCMR joint congress (31 January – 3 February 2018, Barcelona, Spain). The congress was attended by clinicians performing CMR (cardiologists or radiologists), technologists, physicists and engineers from 70 countries. The training session was advertised prior to the meeting on the congress webpage and via email, and all congress attendees could register in advance for the session free of charge. The session was delivered by two biomedical engineers (G.B., S.S.) with a cardiologist (E.G.M.) and it was repeated twice to allow for flexibility within the conference programme.

Course delivery

The course provided

- (a) an overview of the principles of 3D printing, with minimal background on the evolution of the technology particularly in relation to biomedical applications and cardiovascular applications more specifically;
- (b) an overview of the workflow ([Figure 1](#)) from image acquisition and segmentation to model printing and cleaning, including different segmentation strategies and key design considerations;
- (c) practical considerations including an overview of software packages and open-source solutions currently available for image processing, materials compatible with the technology and related costs, and printers currently available on the market and related costs;
- (d) a description of main current cardiovascular applications of the technology, including decision-making, device testing, first-in-man procedures, building experimental setups, communicating with patients and training clinical staff, presenting one or more relevant examples for each through real cases and/or completed studies.

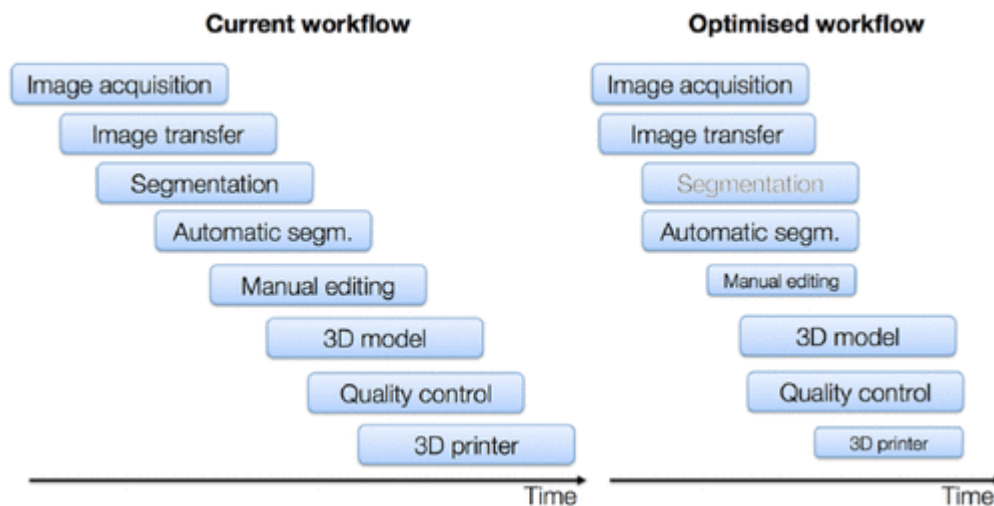


Figure 1. The teaching session included discussing different steps of the current (left) workflow for 3D printing cardiovascular models from image acquisition to printing, as well as discussing possible optimisation of the workflow (right). The latter would entail reducing the time for, and amount of, manual editing of the 3D computer model prior to finalising and exporting to the printer, but also implementing more robust automatic segmentation techniques, and potentially reducing printing time itself (depending on the available printing technology).

These elements of the course were delivered in lecture-style, followed by presenting the participants with a range of 3D printed models of paediatric and adult CHD cases. Models depicted real-life cases based on either CT or CMR data reconstructed using commercial software (Mimics, Materialise, Leuven, Belgium; Simpleware, Simpleware Ltd., Exeter, UK), and they were not all printed on the same machine. In fact, in order to provide a broad overview, participants were shown a selection of fused deposition modelling (FDM), selective laser sintering (SLS), stereolithography (SLA), TangoPlus FullCure[®] and silicone models. Models had been printed previously for different applications and the selection included 15 models, focusing on the technical features of the models rather than on the medical history or clinical characteristics of each case. Models were used to present to participants different printing options, including different colours (e.g. white, transparent, red-and-blue and other colours), different materials (e.g. rigid resin, compliant rubber-like resin and powder-based materials) and different configurations of the models depending on the defect(s) of interest (e.g. being able to open up a model and observing intra-cardiac anatomy vs full solid model to appreciate size and position of great vessels, including the

possibility of using magnets to hold different parts of the model together). To conclude, a case study was presented to summarise the workflow, from case presentation and request of model from the surgeon to model-making and printing, including feedback from different users.¹⁹

Survey and analysis

A short survey comprising of eight questions and designed to be completed in 5–10 min was administered at the end of the session, to capture participants' preferences in relation to course delivery and 3D printing training as well as participants' views on access to and applications of the technology. The survey asked for the participants' professional background and prior experience with 3D printing (if any), the usefulness of the provided training session (on a 5-point Likert-type scale from 'Not useful at all' to 'Extremely useful') and the desire for more training (yes/no answer), including the possibility of longer sessions (yes/no answer) and/or more real-life demonstrations with live model reconstructions. The survey also asked participants for their interest in implementing 3D printing in their practice (answer options: 'Not interested', 'Not interested but it's cool', 'Interested but no set-up available', 'Interested but not enough time' (to implement it), 'Interested') and indicating the areas they considered more relevant in terms of 3D printing applications, checking one or more options from 'Communication', 'Training/teaching', 'Clinical' and 'Research'. Finally, in order to explore different possible set-ups for a 3D printing service, the survey asked participants whether their Centre should be equipped with 3D printing facilities (answer options: 'Yes it already has one', 'Yes, it should have one', 'No, models could be consigned outside for printing' and 'Not sure'). Survey results are presented as counts and proportions.

Results

The 3D printing session was attended by 30 congress participants, of whom 28 completed the survey (93% response rate). Survey responders had a mix of professional backgrounds related to cardiovascular imaging, reflecting the nature of the conference, including CMR fellows/consultants (n = 6) and cardiologists (n = 12), technologists (n = 2), radiologists (n = 5), bioengineers (n = 2) and physicists (n = 1). Participants reported to already have some experience with 3D printing in 39% of the cases, and the majority (79%) expressed interest for additional training. While a large proportion (77%) rated the course as 'very useful' or 'extremely useful' in its current format and no one rated it as 'not useful', 30% of participants expressed desire for longer training sessions and an additional 29% for longer training sessions including live reconstructions. However, 41% of participants considered the course a sufficient introductory session in its format. Considering participants' interest in implementing 3D printing in their practice ([Figure 2](#)), all participants confirmed they would be interested, with most (69%) agreeing on the potential of the technology, and the remainder also agreeing but reporting either not having access to the technology (27%) or not having enough time to dedicate to 3D printing work/research (4%). Participants rated 3D printing as useful for developing research projects (68%), talking to patients (71%), training staff/students (75%) and particularly for gaining additional insight in clinical cases (78%), with 50% of participants ticking all four available options. Finally, when exploring the need for setting up and having access to an in-house 3D printing service, participants mostly confirmed that their centre is either already equipped (39%) or it is currently not equipped, but they felt it would be advantageous if it were (38%). Only 8% participants indicated a preference for consigning model printing to a third party, with 15% remaining undecided.

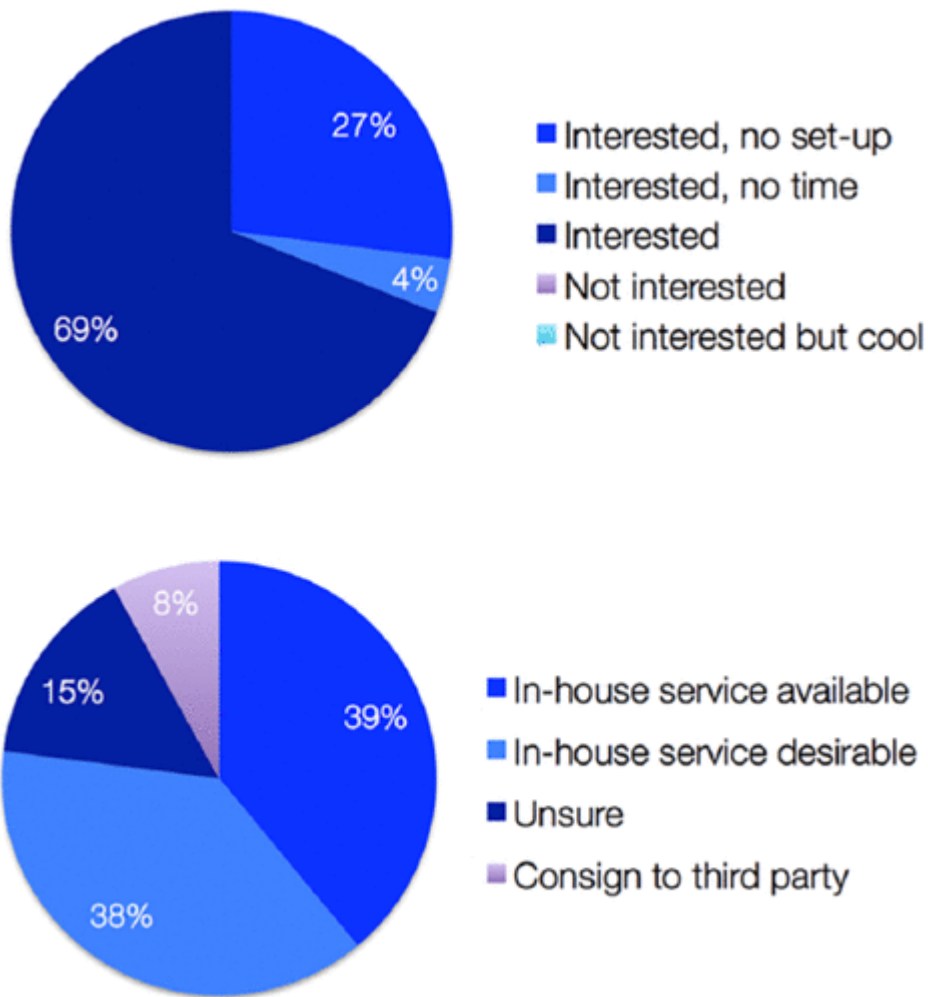


Figure 2. Capturing participants' preferences in relation to availability of a 3D printing in-house service (top) and current availability of or desire for an in-house 3D printing service versus consigning model printing to an external third party (bottom).

Discussion

A relatively short teaching session focused on cardiovascular 3D printing, which can be incorporated in the context of an international cardiovascular imaging congress, where attendees of different professional backgrounds would likely be interested in receiving training on this topic, considering its growing use in clinical practice and research. In our case, the session was attended by cardiologists and imagers as well as technologists and engineers. Professionals with an interest in cardiovascular 3D printing were satisfied with a general introductory session delivered in lecture-style, covering some theoretical aspects, but also summarising practical considerations on image segmentation (and related software), available materials and associated costs, together with an overview of the different applications of the technology. This session was particularly geared towards CHD applications, but an accent could also be put on cardiovascular devices and valves,²⁰ on phantom building and experimental setups, or on patient engagement,²¹ depending on the specific audience.

Our survey revealed that a proportion of participants would have attended a longer session, not only including more in-depth discussion of applications and technical tips, but also including live 3D reconstructions of cases. This suggests the potential for a split training session, with a broader introduction for those with no prior experience in 3D printing but wanting to understand the requirements of implementing the technology at their centre and the basic workflow, followed by a more in-depth and hands-on session where users with some experience could work more interactively on a live case. The latter would imply some degree of preparation before the course, with those interested in the hands-on component attending with a laptop and ensuring the same software was made available to all participants, as well as one or more practice cases.

When considering the different applications of the technology, half of the participants in this survey highlighted the versatile nature of 3D printing in cardiology and cardiac surgery, recognising possible uses for clinical decision-making, training, communication with patients and research. Overall, the use of models for gaining insight into complex cases was rated as the most valuable application of the technology, in part possibly reflecting the nature of the audience. Furthermore, participants unanimously agreed that it would be valuable

to implement 3D printing in their practice. When exploring the possibility of setting up, it emerged that in the majority of cases either participants reported that their centre was already equipped with an in-house facility or they expressed a desire that such a facility should be available, with a minority being indecisive with regards to the optimal set-up or preferring consigning models to an external third party for printing. This is reflective of the increased access to and affordability of the technology in recent years, which currently enables a clinical centre to purchase 3D printing equipment with a more modest investment than just 10 years ago. However, considerations about set-up should also include staffing such a facility and/or collaborations with relevant parties (e.g. biomedical engineers or specialised technicians), as well as governance questions and reimbursement issues depending on different systems. While the survey aimed to capture participants' preferences with regards to in-house printing facilities, the session did not include a full analysis of the costs associated with setting one up. Costs of different materials and printers were presented as part of the session, but other factors (such as person time associated with running an in-house facility) were not discussed, as these were beyond the purposes and scope of the teaching session. These are nevertheless important considerations that, together with a centre's own assessment of their volume of cases, should inform their 3D printing strategy.

The limitations of this study include a small sample, limiting the generalisability of the findings and the ability to undertake any sub-group analyses, and a possible selection bias, with congress attendees with an existing interest or curiosity towards the subject of 3D printing potentially being more likely to participate in the teaching session.

In conclusion, this survey indicated that an effective way to deliver a teaching session on 3D printing would likely include an element delivered in lecture-style and a second, possibly optional, element with more hands-on activities, including image segmentation. Furthermore, a move towards in-house implementation of 3D printing services and/or a desire for in-house 3D printing facilities suggests that this technology may increasingly become an additional tool alongside multimodality imaging, gradually translating into clinical practice.

Acknowledgements

The authors acknowledge the generous support of the British Heart Foundation, The Grand Appeal Bristol Children's Hospital Charity, the Engineering and Physical Sciences Research Council and the European Research Council. This report incorporates independent research from the University Hospitals Bristol and Great Ormond Street Hospital National Institute for Health Research (NIHR) Biomedical Research Centre Funding Schemes. The views expressed in this publication are those of the author(s) and not necessarily those of the NHS, the National Institute for Health Research or the Department of Health. CBD is in part supported by the NIHR Biomedical Research Centre at University Hospitals Bristol NHS Foundation Trust and the University of Bristol.

References

1. Vukicevic M, Mosadegh B, Min JK, et al. Cardiac 3D printing and its future directions. *JACC Cardiovasc Imaging* 2017; 10(2): 171–184.
2. Milano EG, Capelli C, Wray J, et al. Current and future application of 3D printing in congenital cardiology and cardiac surgery. *Br J Radiol* 2019; 92: 20180389.
3. Shelmerdine SC, Simcock IC, Hutchinson JC, et al. 3D printing from microfocus computed tomography (micro-CT) in human specimens: education and future implications. *Br J Radiol* 2018; 91(1088): 20180306.
4. Acar P, Hadeed K and Dulac Y. Advances in 3D echocardiography: from foetus to printing. *Arch Cardiovasc Dis* 2016; 109(2): 84–86.
5. Bhatla P, Tretter JT, Ludomirsky A, et al. Utility and scope of rapid prototyping in patients with complex muscular ventricular septal defects or double-outlet right ventricle: does it alter management decisions? *Pediatr Cardiol* 2017; 38(1): 103–114.
6. Biglino G, Capelli C, Koniordou D, et al. Use of 3D model of congenital heart disease as an education tool for cardiac nurses. *Congenit Heart Dis* 2017; 12: 113–118.
7. Costello JP, Olivieri LJ, Krieger A, et al. Utilizing three dimensional printing technology to assess the feasibility of high-fidelity synthetic ventricular septal defect models of simulation in medical education. *World J Pediatr Congenit Heart Surg* 2014; 5: 421–426.
8. Biglino G, Giardini A, Baker C, et al. In vitro study of the Norwood palliation: a patient-specific mock circulatory system. *ASAIO J* 2012; 58(1): 25–31.
9. Biglino G, Capelli C and Wray J. 3D-manufactured patient specific models of congenital heart defects for communication in clinical practice: feasibility and acceptability. *BMJ Open* 2015; 5(4): e007165.
10. Biglino G, Cosentino D, Steeden JA, et al. Using 4D cardiovascular magnetic resonance imaging to validate computational fluid dynamics: a case study. *Front Pediatr* 2015; 3: 107.
11. Figliola RS, Giardini A, Conover T, et al. In vitro simulation and validation of the circulation with congenital heart defects. *Prog Pediatr Cardiol* 2010; 30(1–2): 71–80.
12. Bhatla P, Tretter JT, Chikkabyrappa S, et al. Surgical planning for a complex double-outlet right ventricle using 3D printing. *Echocardiography* 2017; 34(5): 802–804.
13. Biglino G, Koniordou D, Gasparini M, et al. Piloting the use of patient-specific cardiac models as a novel tool to facilitate communication during clinical consultations. *Pediatr Cardiol* 2017; 38: 813–818.

14. Riggs KW, Dsouza G, Broderick JT, et al. 3D-printed models optimize preoperative planning for pediatric cardiac tumor debulking. *Transl Pediatr* 2018; 7(3): 196–202.
15. Chepelev L, Wake N, Ryan J, et al. Radiological Society of North America (RSNA) 3D printing Special Interest Group (SIG): guidelines for medical 3D printing and appropriateness for clinical scenarios. *3D Print Med* 2018; 4(1): 11.
16. Abudayyeh I, Gordon B, Ansari MM, et al. A practical guide to cardiovascular 3D printing in clinical practice: overview and examples. *J Interv Cardiol* 2018; 31(3): 375–383.
17. Mitsouras D, Liacouras P, Imanzadeh A, et al. Medical 3D printing for the radiologist. *Radiographics* 2015; 35(7): 1965–1988.
18. Otton JM, Birbara NS, Hussain T, et al. 3D printing from cardiovascular CT: a practical guide and review. *Cardiovasc Diagn Ther* 2017; 7(5): 507–526.
19. Biglino G, Moharem-Elgamal S, Lee M, et al. The perception of a three-dimensional-printed heart model from the perspective of different stakeholders: a complex case of truncus arteriosus. *Front Pediatr* 2017; 5: 209.
20. Muraru D, Veronesi F, Maddalozzo A, et al. 3D printing of normal and pathologic tricuspid valves from transthoracic 3D echocardiography data sets. *Eur Heart J Cardiovasc Imaging* 2017; 18(7): 802–808.
21. Lau IWW, Liu D, Xu L, et al. Clinical value of patient-specific three-dimensional printing of congenital heart disease: quantitative and qualitative assessments. *PLoS ONE* 2018; 13(3): e0194333.