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Cover Sheet

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Abstract

Objective: To develop a participatory approach in the evaluation of 3D printed patient-specific models of congenital heart disease (CHD) with different stakeholders who would potentially benefit from the technology (patients, parents, clinicians and nurses).

Methods: Workshops, focus groups and teaching sessions were organized, targeting different stakeholders. Sessions involved displaying and discussing different 3D models of CHD. Model evaluation involved response counts from questionnaires and thematic analysis of audio-recorded discussions and written feedback.

Results: Stakeholders' responses indicated the scope and potential for clinical translation of 3D models. As tangible, three-dimensional artefacts, these can have a role in communicative processes. Their patient-specific quality is also important in relation to individual characteristics of CHD. Patients indicated that 3D models can help them visualise "what's going on inside". Parents agreed that models can spark curiosity in the young people. Clinicians indicated that teaching might be the most relevant application. Nurses agreed that 3D models improved their learning experience during a CHD course.

Conclusion: Engagement of different stakeholders to evaluate 3D printing technology for CHD identified the potential of the models for improving patient-doctor communication, patient empowerment and training.

Practice Implications: A participatory approach could benefit the clinical evaluation and translation of 3D printing technology.

Keywords

Patient and public involvement; rapid prototyping; personalized medicine; congenital heart disease.

1. Introduction

Patient-doctor communication is recognised as an essential part of clinical practice (Travaline *et al.* 2005). Improved communication strategies can aid in achieving what has been defined as a triple aim of improving quality of care, reducing costs and enhancing patient experience (Gordon *et al.* 2015). New technologies can enrich and facilitate such communication strategies, particularly by improving connectivity and enabling a better flow of information (Gordon *et al.* 2015). One technology that can play a role in this context is three-dimensional (3D) printing technology, i.e. the capability of manufacturing a suitable input file into a 3D object by printing it layer by layer at a fine resolution. The potential benefits of 3D printing in medicine are indeed multiple, ranging from the educational domain to improving decision-making, from patient-specific implants to aiding in communication (Biglino *et al.* 2011; Costello *et al*. 2015).

An area that lends itself to the use of a personalised approach is congenital heart disease (CHD). This is mainly due to a) the anatomical complexity and small dimensions of congenital defects (vascular and intra-cardiac) and b) the unique nature of the cases that do not warrant a standardised approach but rather a patient-specific approach. In particular, it could be argued that by using a 3D replica to better visualise the congenital defect being discussed, these tools could improve the quality of communication between clinicians and patients and their families. The *invisible* nature of CHD and its complexity are known to lead to misperceptions and knowledge gaps in patients that are affected (Verstappen *et al.* 2006; Chiang *et al.* 2015). The potential of 3D printing technology to make the invisible *visible* can have beneficial repercussions on communication strategies and, in turn, on understanding of CHD.

Little evidence has been collected to this end. One recent study (Biglino *et al.* 2015) targeted a group of parents of children with CHD to evaluate conventional communication vs. communication aided by a 3D model. This study showed that parents appreciated and responded well to the models. They found models more immediate than medical images and more helpful for their understanding of the defect, but their short-term knowledge of the main features of the CHD did not appear to improve as a result of exposure to the models. In the same study, cardiologists equally valued the 3D replicas, and found them useful in discussing the defect with the families; however, consultations had a longer duration on average than when models were not used. As both expert and non-expert users demonstrated interest in the technology, more research is warranted to evaluate its full value in aiding communication.

The aim of this study was to collect feedback from representative stakeholders in order to better inform the next steps in the evaluation of clinical translation of 3D printing technology for CHD.

2. Literature review

Early evidence of the effects of good patient-doctor communication included the positive impact on patient outcomes such as pain and anxiety; physiological parameters such as blood pressure and glucose levels; as well as patient satisfaction and patient adherence to treatment (Stewart *et al.* 1999). A review of the subject (Ha and Longnecker 2010) detailed several areas for improving communication, including: communication skills and training, collaborative communication (i.e. reciprocal two-way exchange), addressing unspoken conflicts (e.g. in paediatric palliative care), and acknowledgement of divergent beliefs. The literature also discusses the shift from a more 'paternalistic' approach to shared decision-making and patient empowerment

(Teutsch 2003). Indeed, amongst key tasks in communicating with patients, it is important that the physician is able to elicit the patient's main problems and perception of these, as well as tailoring information and verifying the patient's understanding of the problem itself (Maguire and Pitcealthly 2002).

Research in health is continually being shaped by the involvement of patients and the public (PPI) in participatory paradigms and an approach based on PPI has value for assessing the potential of 3D printing technology and its specific implementation in the field of CHD. One theory which supports such a participatory approach is the theory of social construction of technology, which posits that technology is shaped by human action rather than being a determinant of it. Furthermore, proponents of the theory argue that in order to understand how a technology is used it is necessary to understand how it is embedded in its social context. One of the core concepts is that of interpretative flexibility, whereby each technological artefact is recognised as having different meanings and interpretations for different groups of people (e.g. users, designers etc).

Within the wider literature on health and illness there are many examples of how a participatory approach has influenced technological design, and ultimately health outcomes. One example is the recent development of a mobile health application to promote medication adherence and enhance communication about medical management in solid organ recipients (Shellmer et al. 2016). The investigators in this latter study employed principles of user-centred design to iteratively develop and test the application, resulting in a product which adolescents expressed an interest in using and high levels of user satisfaction. In a recent review of adolescents' use of mobile and tablet applications to support their own management of their chronic health conditions, a consistent finding was that adolescents contribute to the design of the

applications (Majeed-Ariss *et al.* 2015). Health professionals are also increasingly being engaged in the development of technology, which is recognised as important if the technology is going to be embedded into clinical practice (Aldiss *et al.* 2010).

3. Materials and methods

We identified four groups of stakeholders who would be able to make salient contributions to the evaluation of 3D printing of CHD:

a) Patients with CHD, i.e. young people attending clinics, who are starting to take more responsibility for their own health and for whom it is crucial to enhance the quality of communication and ensure the best possible understanding of the condition for lifestyle adjustments and overall awareness;

b) Parents of patients with CHD, who are also faced with the challenges of understanding the life-long complications of repaired CHD and caring for their children, particularly at younger ages;

c) Clinicians, including cardiologists and cardiac surgeons, who can potentially use 3D patient-specific models to facilitate communication, as well as in the planning of different procedures and as an aid in decision-making;

d) Trainees, particularly nurses, who require an in-depth knowledge of CHD morphology and complications to care for these often medically complex patients.

Four workshops, one for each stakeholder group, were convened to collect user views on 3D printed models of CHD. Each workshop was audio-recorded and contemporaneous notes made during the session. Ethical approval for the study was received from the National Research Ethics Service and all participants provided written consent for their participation and the use of the audio-recordings, if applicable.

a) Patients with CHD

A group of patients with CHD (n=13) was invited from the cardiac transition clinic at our Centre. All patients (age range 14.8-18.5 years, 9 males) had repaired complex congenital heart disease, such as transposition of the great arteries, tetralogy of Fallot, coarctation of the aorta and Fontan-type circulation. Patients were invited to a 2-hour workshop. At the beginning of the workshop they received a brief explanation about how 3D patient-specific models are manufactured, starting from processing of cardiovascular magnetic resonance (CMR) image data. They were then invited to create 3D heart models using play-doh, as an icebreaker activity. Finally, they were shown a range of 3D models of CHD, showcasing different defects and manufactured using different materials (summarised in Table 1). <INSERT TABLE 1 ABOUT HERE.> Samples of the models are shown in Figure 1. Patients were asked to freely discuss features of all the models they were shown and they were guided by two workshop facilitators, one of whom was an adolescent clinical nurse specialist and the other a biomedical engineer, during the discussion.

<INSERT FIG. 1 ABOUT HERE.>

b) Parents of patients with CHD

Running concurrently with the patient workshop (group a), a second group was formed, composed of parents of patients with CHD (n=15, 9 mothers). Parents received the same brief explanation about how 3D patient-specific models are manufactured with the young people and were then invited into a separate room, in which they were first guided to discuss aspects of using 3D models of CHD in clinical practice, including:

- Any potential anxieties they had regarding their child's response when he/she is shown a 3D model of his/her CHD;

- Whether they thought 3D models could engage their child; and

- Whether they had a preference for a lesion-specific model or a patient-specific model

Parents were then shown the same range of models as the young people (Table 1) and invited to discuss features of the models. The workshop discussion was facilitated by two biomedical engineers.

c) Clinicians

A group of clinicians (n=14, 12 male) was invited to a 3-hour workshop titled "*How to transform your 2D clinical images into a 3D printed model to guide procedures*". The workshop discussed technical aspects related to image processing and consequent creation of 3D models. Clinicians worked in fields related to cardiology (e.g. consultant cardiologists, CMR fellows, cardiology specialist registrars) and were asked to complete a brief questionnaire prior to and at the end of the workshop. The questions focused on evaluating the clinicians' perception of 3D models of CHD and their willingness to adopt this tool in clinical practice. Questions comprised forced choice, Likert scale and multiple-choice responses. Questions included whether they had previously used a 3D model and what kind of image data they had access to; would they use a patient-specific model in their practice; their level of agreement about whether 3D patient-specific models are helpful for planning interventions, teaching and/or testing devices; and a ranking of the most relevant potential applications, including teaching, planning procedures, communication with patients, and research.

d) Nurses

A group of nurses (n=11, 11 female), who attended a foundation course in adolescent cardiac care at a specialist paediatric hospital, was asked to complete a questionnaire about the features of 3D models of CHD at the end of the course. The nurses were shown 8 models derived from patient-specific CMR data, representing the following anatomical arrangements: normal cardiac anatomy; repaired transposition of the great arteries; aortic coarctation; repaired tetralogy of Fallot; pulmonary atresia with intact ventricular septum; and hypoplastic left heart syndrome at all three stages of palliation (i.e. post Norwood procedure, post Glenn, and post total cavopulmonary connection). All models (Figure 2) were available to look at throughout the course and, at the end of the course, the nurses were asked to complete a short questionnaire to assess the usefulness of the models from a learning perspective. Questions included their level of agreement about whether 3D patient-specific models added to the learning experience; whether models are more informative than diagrams and drawings; whether 3D models are helpful for appreciating anatomical dimensions, spatial orientation of anatomical features, anatomical complexity, treatment and care for CHD patients; and a ranking of which models were most useful. Participants were also invited to provide additional free text feedback. <INSERT FIG. 2 ABOUT HERE.>

Manufacturing the 3D models

All models used in this study were patient-specific and derived from anonymised CMR data of patients with the condition of interest. Imaging data were processed with commercial software (Mimics, Materialise, Leuven, Belgium), as described previously (Schievano *et al.* 2007). The processed 3D data were exported in a stereolithography (.stl) format compatible with 3D printers. While models were specifically printed using

a range of different materials to identify preferences of participants in the patient and parent focus groups (Table 1), and this range of models was also shown to the clinicians' group, the models that were used for teaching purposes with the nurses were all printed in white nylon as a neutral option, with the objective of focusing on the anatomy itself in this case.

Analysis of workshop data

The quantitative data from the questionnaires were analysed using descriptive statistics (frequencies, means). Participants' free text comments were analysed using thematic analysis. Free text comments from the questionnaires were entered into a spreadsheet and two authors independently coded the data before grouping the codes into meaningful themes. The authors met and agreed a list of themes and checked back with the data to ensure that the themes accurately reflected the data. For the recordings from the workshops with patients and parents, a similar approach was adopted with two authors listening to the recordings several times, identifying codes and grouping the codes into themes.

4. Results

a) Patients

Patients engaged well in the workshop, following a successful icebreaker activity involving making 3D hearts with play-doh (Figure 1). All participants were actively involved in the conversation, did not restrain from commenting when shown a model and did not openly show anxiety or discomfort in discussing 3D models. In discussing the models (Figure 1), patients specifically spoke about the value of the models in

enhancing their understanding of their heart condition. They reported that the models were "clearer than CMR scans" and that they "help [to] visualise what's going on inside". Patients also thought 3D models could be "useful for explaining [their heart condition] to [their] siblings". Patients unanimously agreed that the addition of computational/visual information on a computer to that provided by the 3D rapid prototyping model would be desirable; however, when asked to choose between a 3D rapid prototyping model and a virtual one, the majority (10 out of 13) opted for the 3D rapid prototyping model.

With regard to the features of the models, young people reported that transparent models "help you imagine blood travelling through the arteries". They also suggested the use of several colours ("not just red and blue") to label different anatomical structures (e.g. heart chambers, vessels) and the defect itself. One participant commented that "red can be shocking". Almost all patients (12 out of 13) agreed that a real size model is more informative than an enlarged version.

b) Parents

Parents also engaged well in the discussion with the workshop facilitators (Figure 3), providing eloquent responses, generously sharing their experience in a relaxed conversation. Only 2 out of 15 parents expressed some concern at the prospect of their children being shown their 3D patient-specific model. The focus of their concern was that their children could potentially be distressed at the sight of a realistic model. Parents unanimously agreed that models could stimulate curiosity and engage their children at the time of transition clinic. They preferred the idea of a patient-specific model rather than a lesion-specific model, with several saying that the diagnosis of their children is "complex congenital heart disease" and therefore that a lesion-specific

model would not be a sufficient representation. Parents also indicated that it would be desirable to have a control model (i.e. normal cardiac anatomy) to further highlight what components/dimensions are different or are affected in their child.

<INSERT FIG. 3 ABOUT HERE.>

Regarding the features of the models themselves (Table 1), 13 out of the 15 parents did not have a preference for any one of the three white aortic models, but 2 participants did not like the white models printed in Nylon ("they feel too fragile"), and when shown the four models of the right ventricular outflow tract made in different materials, 13 out of 15 parents preferred those in TangoPlus® (i.e. rubber-like) as they "feel more real". They unanimously agreed that transparent models would be helpful to show the route of a catheter or the position of a valve. They also unanimously agreed that the red colour did not add information for a single anatomical component (e.g. aorta), and the lesion could actually be better appreciated on white models; however, when more than one anatomical component was included in the model (e.g. right and left heart), a colour model (i.e. red and blue) was thought to be better. They indicated that they were familiar with red and blue models from school, books and pamphlets.

From a methodological perspective, parents indicated that any future research to study models with their children should be somewhat interactive, e.g. using iPads to show visual information to a technologically competent young generation.

c) Clinicians

Prior to the workshop, clinicians reported that they did not feel very well informed about 3D printing (average self-reported knowledge = 3.9±1.7 on a scale 1-10). Four clinicians reported that they had used a 3D model previously. When discussing the usefulness of patient-specific models for practicing/planning interventions, teaching

and testing new devices, clinicians generally agreed or strongly agreed that models could be a valuable tool (Figure 4), particularly for teaching purposes and less so for testing new devices. <INSERT FIG. 4 ABOUT HERE.> When asked whether they would use a 3D model in their own practice, 7 out of 14 strongly agreed and 6 out of 14 agreed, with only one participant remaining neutral. Interestingly, clinicians ranked teaching as the most relevant potential application of 3D models, while communication was ranked as least relevant (Figure 5). <INSERT FIG. 5 ABOUT HERE.>

d) Nurses

Overall, nurses reported that the use of patient-specific models improved their leaning experience (9 agreed, 2 strongly agreed) and they found models to be more informative than diagrams and sketches (9 agreed, 2 neutral). Nurses agreed that 3D models are helpful for understanding the anatomy (11 out of 11), spatial orientation (9 out of 11) and complexity post surgical repair (8 out of 11). However, they were more ambiguous with regard to how helpful they thought the models were as an aid to understanding treatment and care for patients with CHD (6 out of 11). When comparing patient-specific models with generic (or lesion-specific) models the response was inconclusive, with some nurses agreeing and some disagreeing that patient-specific models provide more information, and 3 out of 11 nurses found the patient-specific models somewhat confusing in this regard. In terms of the range of CHDs that were modelled, all were found to be useful or very useful, with those conditions requiring understanding of the pulmonary valve and right ventricular outflow tract scoring as least helpful (Table 2). While the models were all purposefully printed in white nylon for this group of nurses, five participants pointed out in their written feedback that different colours would have been helpful.

<INSERT TABLE 2 ABOUT HERE.>

5. Discussion and conclusion

5.1. Discussion

Rapid prototyping technology can have a revolutionary impact in medical practice, although it still poses regulatory concerns as well as ethical and technical challenges (Maruthappu and Keogh 2014). The possibility of replicating the human anatomy in 3D can potentially help patients and their families visualise complex anatomical features, improve their understanding of potential complications and have a better appreciation of the condition overall. This could be particularly relevant for the area of congenital heart disease (CHD), where the complexity of both anatomy and repairs warrants a patient-specific approach, which is an intrinsic advantage of rapid prototyping medical models. Intra-cardiac and/or vascular arrangement after CHD repair can be very different from normal cardiovascular anatomy and can vary considerably between patients with the same diagnosis; because of its high three-dimensionality, spatial and dimensional understanding from images may be very limited, particularly for non-expert users; vessel dimensions can also be very small (< 1 cm) in young patients. Preliminary research (Biglino *et al*. 2015) with parents of patients with CHD and their cardiologists showed that the models were generally liked by participants, although some results were more controversial, such as the lack of improvement in short-term parental knowledge and the extended duration of consultations. It is evident that more in-depth studies are needed to further elucidate the clinical translation of this technology.

Within the framework of the theory of social construction of technology, a participatory approach is important for the implementation of this new technology. In the current study we engaged with both non-expert (i.e. patients and their parents, separately) and expert users (i.e. nurses and clinicians with a specialist background in paediatric cardiology or cardiac imaging) as key stakeholders in this technology.

Patients agreed that models can be useful for improving their understanding, qualitatively, of their heart condition. This understanding can be further enhanced if the model is printed in real size (rather than scaled to an enlarged size, e.g. to maximise insight into the defect). They felt that 3D models could help in the communication process not just with clinicians, but also with other people such as other healthcare professionals (e.g. health visitor), friends and siblings. As a technology competent young generation, teenage patients liked the idea of potentially accessing additional information virtually (e.g. results from computational simulations shown on a screen). However, the majority still reported that if they had to choose between a virtual and a physical rapid prototyping model, they would prefer the physical model. We suggest that this might be related to the fact that not only does a 3D rapid prototyped model make *visible* something that is *invisible* (i.e. their CHD), but it also renders it *tangible*. The role of tangible artefacts in healthcare has been discussed previously, particularly in relation to supporting collaborative work and the effect on decision-making, within the framework of distributed cognition (Xiao 2005). In general terms this aspect relates to the *materiality* of the artefacts and the role of artefacts in communicative behaviours (Dant 2005).

Elicitation of parents' perspectives in the current workshop revealed that parents are generally not worried about the possibility of young people being shown their own models and potentially being shocked by them. In fact, they all thought that

patient-specific models could stimulate curiosity in young people and prompt them to ask questions. One important point raised by the parents was that they preferred a patient-specific model to a generic, lesion-specific model. In particular, they felt that a generic model of the lesion may not fully represent all of the features of their children's anatomy, whereas a patient-specific model is a more useful tool in this regard.

With regard to the actual models, both patients and parents liked transparent models, with patients commenting that transparency can help in imagining blood flowing through the vasculature and parents adding that it can be helpful in visualising the position of a device when discussing a procedure with a clinician. Parents appreciated compliant (i.e. rubber-like) models in particular, as they deemed them to be "more realistic", while patients were more resistant to this kind of model and in fact some considered them to be "too realistic". The possibility of using this kind of model, which can have other useful research applications (Biglino *et al.* 2013), should be explored further. Both patients and parents also liked colourful (i.e. red and blue) models, with which they were somewhat familiar, but they were not considered definitely superior to white models, particularly for those models that only involved one side of the circulation (e.g. left ventricle and aorta). Regarding the use of colours, patients suggested that using multiple colours might be helpful for highlighting different structures and the defect(s) being discussed, which would be feasible from a technical point of view (Yoo *et al.* 2014).

Clinicians responded positively with respect to the use of 3D patient-specific models in clinical practice, particularly for teaching applications, which was ranked as the most relevant application of 3D models. Rapid prototyping models could be a valuable training tool, without the need for specimens, for a library of congenital heart defects. A recent study reported positive results in this regard, whereby 29 premedical

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and medical students were exposed to a simulation-based educational curriculum using 3D heart models, particularly focusing on the study of ventricular septal defects (VSDs). Students reported statistically significant improvements in knowledge acquisition, knowledge reporting, and structural conceptualization of VSDs (Costello *et al.* 2014). In contrast, in the current study use of the 3D model as an aid to communication was not prioritised by clinicians, and was ranked as least relevant amongst possible applications of 3D models. This might be due to the fact that clinicians still rely on medical images and sketches for communication purposes, but may also be reflective of clinicians' confidence in their own consultation style (Williams *et al.* 1998). Whilst this does not undermine the communication potential of 3D patient-specific models, it rather suggests that further engagement with the expert user is needed to determine how best to implement models as communication tools in clinical practice.

This study supports using a participatory approach for the implementation of a novel tool (i.e. 3D patient-specific models). In general, PPI can be extremely valuable for many aspects of the research process, including prioritising research questions, providing the user perspective in steering groups, improving consent rates and ultimately enhancing the relevance, validity, quality and success of clinical research (Brett *et al.* 2014; Gamble *et al.* 2014; Taylor *et al.* 2015). From a PPI perspective this study shows that the way in which groups are organised is important to ensure their success and hence gather relevant information to structure future studies and prioritize questions. The workshops with patients and parents were run successfully in an informal setting by bioengineers involved with 3D printing technology and an adolescent nurse specialist who knew the young people. Similarly, a workshop focused on more technical aspects related to medical imaging and 3D printing successfully

engaged a group of clinicians, in a more formal setting, again facilitated by bioengineers involved with 3D printing technology as well as experts in CMR physics. The workshop with the nurses was also run in a more formal setting, within the context of a course they were attending, with nurses generally responding well and indicating 3D patient-specific models as useful tools for their learning and for understanding CHD anatomy. While this highlights the different settings chosen for different groups, the approach remains multidisciplinary throughout, involving bioengineers, clinicians, experienced nurses, and a psychologist in the organisation of the groups, and planning and running of the activities.

One interesting aspect that should be explored in future work is the idea of a *co-researcher*, particularly for young people with CHD, to improve the evaluation of this novel tool and explore further ways in which young people may use it, such as in providing informed consent/assent for medical procedures. This is based on the assumption that young people would feel more comfortable if a survey was administered by a person of similar age and/or a peer (in this case, another patient with CHD). As discussed in the literature, involving young people in study design, set-up and naming can influence the acceptability of the study and consent procedures, resulting in higher acceptance rates (Boote *et al.* 2010). Methodologically, it has been noted that a shift from research *on* children, through research *with* children to research *by* children is accompanying the changes in adult-child power and participation agendas (Kellett 2005). The involvement of young people as participatory researchers can lead to improved access to other young people. This approach can have the advantage of providing 'insider knowledge', but also the disadvantage that the participants' potential emotional involvement in the subject-matter can be a cause of tension. Participatory research has also been identified as 'empowerment research' and has been proposed as

a practice that should be recognised and fostered (Toronto Group 2005). In terms of the sensitivity of 'empowerment research', guidelines have been put forward on how to involve children and young people in research; in the UK, this has been curated by the National Children's Bureau (see: www.participationworks.org.uk). Patients and parents in our study responded favourably to the idea of a co-researcher, supporting the fact that this approach warrants further research and piloting.

5.2. Limitations

The small sample size of each of the stakeholder groups was small, precluding statistical analysis and also potentially limiting the generalizability of the findings.

5.3. Conclusion

This paper presented results describing the engagement of different stakeholders with the clinical translation of 3D printing technology for identifying model features and research questions of interest, particularly with regard to congenital heart disease. Benefits of 3D printing for CHD are, at present, only projected. In an effort to gather evidence to support or contradict their clinical use, PPI can provide access to important feedback from different stakeholders. Furthermore, a PPI-based approach in the evaluation and translation of 3D printing technology may in turn increase patient empowerment, improve patient-doctor communication and provide increased access to a new tool for teaching and training purposes. Future studies with larger sample sizes to enable appropriate statistical analysis should include a participatory approach in their design and ultimately focus on evaluating the actual clinical usefulness of the technology, which would include measuring variables such as patient satisfaction,

patient adherence/loss to follow-up, lifestyle adjustments, appropriateness of exercise levels, and, from the clinicians' perspective, the impact on the decision-making process.

Conflict of interest

None to declare

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Table 1

List of 3D cardiovascular models that were given to patients with CHD and parents of the patients to discuss, showcasing different parts of the anatomy and manufactured using different materials and colours.

ANATOMY	MATERIAL	COLOUR
	SLA resin (smooth finishing)	White
Aorta	Thermoplastic (rougher finishing)	White
	Nylon (selective laser sintering technique)	White
	SLA resin (smooth finishing); hollow lumen	White
Right ventricular outflow tract	Thermoplastic (rougher finishing); filled lumen	White
	Watershed® resin (smooth finishing)	Transparent
	TangoPlus® (rubber-like)	Opaque
Aorta + left ventricle	Powder print	Blue
Pulmonary artery + right ventricle	Powder print	Red

Table 2

Nurses ranking of 3D patient-specific models' usefulness for understanding the anatomy of different conditions, on a scale 1-7 (where 7 = extremely useful).

MODEL	RANKING	SCORING (MEAN±SD)
Aortic coarctation	1	6.0±0.8
Hypoplastic left heart syndrome (stage I)	2	5.8±0.8
Control anatomy (healthy anatomy)	3	5.7±1.2
Hypoplastic left heart syndrome (stage II)	4	5.6±0.5
Hypoplastic left heart syndrome (stage III)	5	5.5±0.5
Transposition of the great arteries	5	5.5±1.3
Pulmonary atresia	7	4.9±1.2
Tetralogy of Fallot	8	4.8±1.1

Figure legends

Figure 1: (A) Engagement activity with young people making 3D heart with play-doh and (B) producing a range of 3D heart models as an ice-breaking activity for a workshop with CHD patients. (C) Collecting feedback from patients with CHD on paper tablecloths, discussing different models (in this picture: three different models of right ventricular outflow tracts).

Figure 2: Models manufactured for training purpose, as shown to a group of nurses, representing a range of congenital heart defects. Models not in scale but for illustrative purposes only. (TGA = transposition of the great arteries, ToF = tetralogy of Fallot, CoA = coarctation of the aorta, HLHS = hypoplastic left heart syndrome, TCPC = total cavopulmonary connection)

Figure 3: A range of models is prepared for being discussed amongst a group of parents of patients with CHD.

Figure 4: Clinicians rating of usefulness of 3D patient-specific models before and after a workshop discussing 3D modelling from medical imaging.

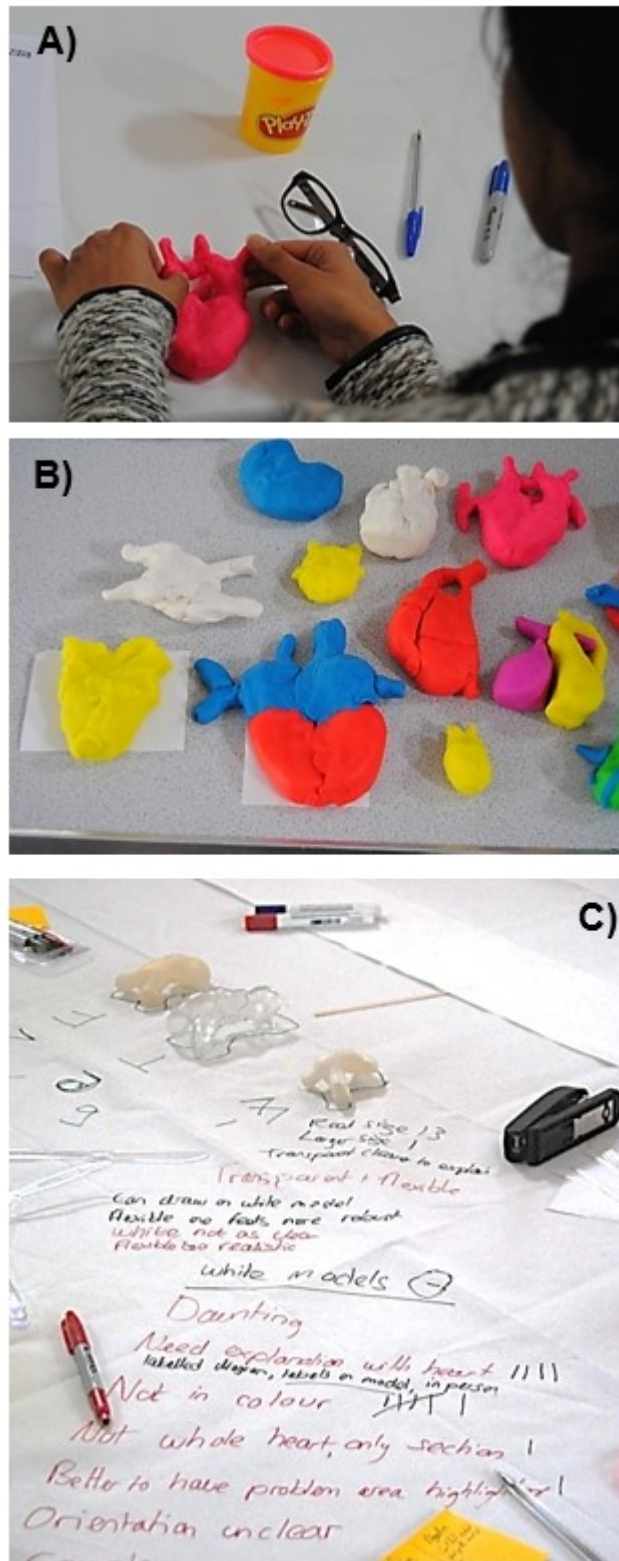**Figure 5:** Clinicians' ranking of relevant applications of patient-specific models

Figure 1
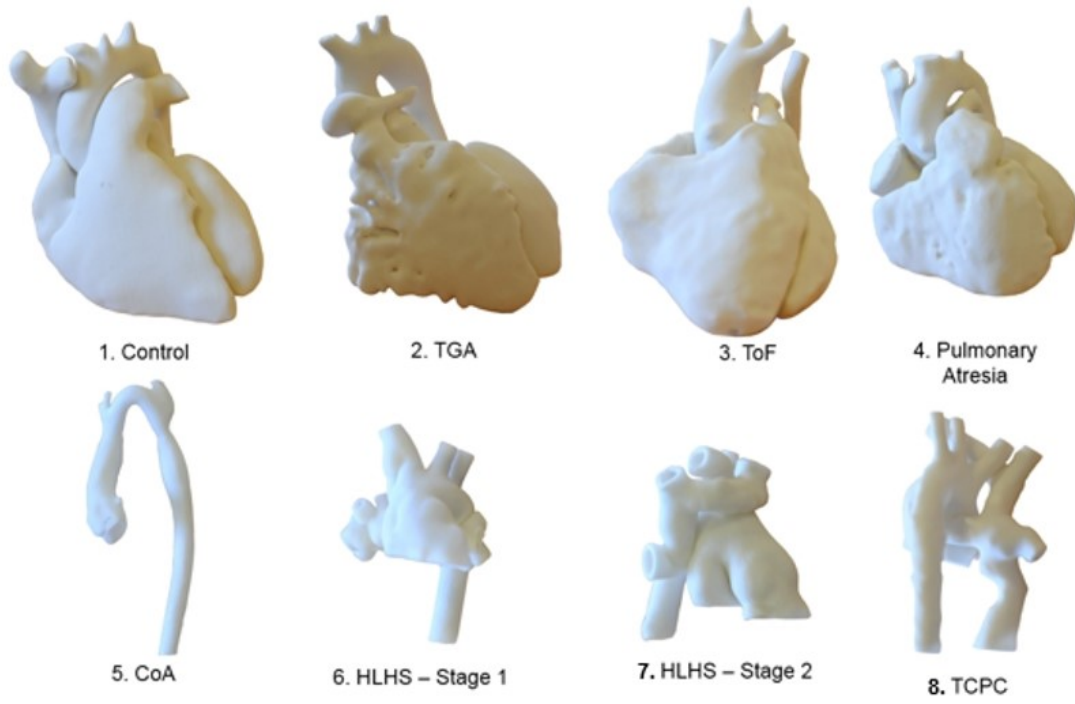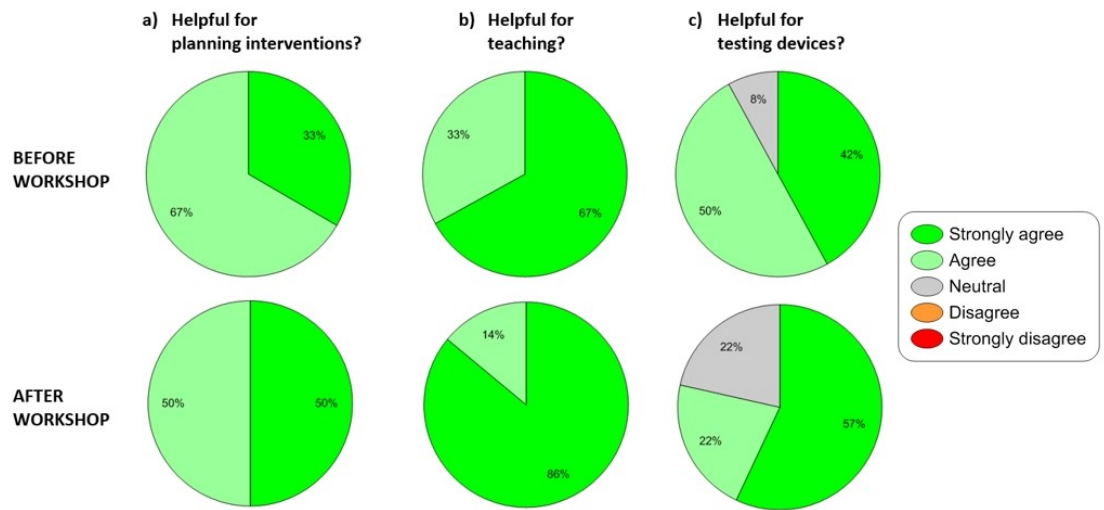
Figure 2

1. Control   2. TGA   3. ToF   4. Pulmonary Atresia

5. CoA   6. HLHS – Stage 1   7. HLHS – Stage 2   8. TCPC

Figure 3

Figure 4

Figure 5