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ORIGINAL ARTICLE

3D Modelling and Printing Technology to Produce Patient-Specific 3D Models

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Background A comprehensive knowledge of mitral valve (MV) anatomy is crucial in the assessment of MV disease. While the use of three-dimensional (3D) modelling and printing in MV assessment has undergone early clinical evaluation, the precision and usefulness of this technology requires further investigation. This study aimed to assess and validate 3D modelling and printing technology to produce patient-specific 3D MV models.

Methods A prototype method for MV 3D modelling and printing was developed from computed tomography (CT) scans of a plastinated human heart. Mitral valve models were printed using four 3D printing methods and validated to assess precision. Cardiac CT and 3D echocardiography imaging data of four MV disease patients was used to produce patient-specific 3D printed models, and 40 cardiac health professionals (CHPs) were surveyed on the perceived value and potential uses of 3D models in a clinical setting.

Results The prototype method demonstrated submillimetre precision for all four 3D printing methods used, and statistical analysis showed a significant difference ($p < 0.05$) in precision between these methods. Patient-specific 3D printed models, particularly using multiple print materials, were considered useful by CHPs for preoperative planning, as well as other applications such as teaching and training.

Conclusions This study suggests that, with further advances in 3D modelling and printing technology, patient-specific 3D MV models could serve as a useful clinical tool. The findings also highlight the potential of this technology to be applied in a variety of medical areas within both clinical and educational settings.

Keywords Mitral valve • 3D modelling • 3D printing • Patient-Specific

Introduction

Advances in imaging techniques have allowed for the visualisation of two dimensional (2D) data as three dimensional (3D) representations [1]. Three dimensional modelling is the process of creating a virtual 3D reconstruction of a physical surface or object from imaging data [2,3]. A virtual 3D model can be converted into a physical 3D model using 3D printing, a rapidly growing technology that allows for the fabrication of objects with various geometries in a layer-by-layer manner [4]. Traditionally, this technique has been used for industrial applications, as well as in medicine for fields such as plastic surgery, orthopaedics and dentistry. The advantage of this in medicine is that it provides a tangible structure that clinicians can use to examine patient-specific anatomy and plan procedures without having to directly inspect the patient [5].

In recent years, there has been a growing interest in the use of 3D modelling and printing in cardiovascular medicine. To date, most cardiovascular applications of this technology have been to generate 3D models of either the aorta, the

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coronary arteries, or the entire heart to assess congenital heart defects and cardiac tumours [6,7]. However, the use of 3D models in mitral valve (MV) assessment has also undergone early clinical evaluation [2,5,6,8–15]. Of the four heart valves, the MV is the most commonly affected by disease [16]. Given the prevalence of MV disease in the elderly population [17], decisions regarding treatment options are particularly important, owing to the higher risk of morbidity resulting from intervention [18]. Repair of the MV is preferred over replacement [8,16] and for these procedures to be successful, a comprehensive knowledge of patient-specific MV anatomy is crucial. However, the complexity of the MV presents a challenge to conventional repair surgery [12,19]. Consequently, there is much interest in newer technology such as 3D modelling and printing to assess MV characteristics.

While imaging is a standard procedure for the diagnosis of MV disease, the benefits of 3D MV modelling have been recognised and discussed in the literature [2,3]. However, there is limited data on the precision of 3D modelling and printing technology and this needs further evaluation. Therefore, the purpose of this study was to assess and validate 3D modelling and printing technology to produce patient-specific 3D MV models.

Materials and Methods

Ethical clearance from St Vincent's Hospital HREC (14/262) was obtained to collect and use patient imaging data for this study.

Prototype Method for MV 3D Modelling and Printing

A MV 3D modelling and printing prototype method was produced by reconstructing the MV from computed tomography (CT) scans of a plastinated human heart. Using Mimics® (Materialise, NV) Research 18.0 and 3-matic® Research 10.0, the MV apparatus was segmented through thresholding and a virtual 3D model was calculated. The model was then 3D printed using fused deposition modelling (FDM), stereolithography (SLA), selective laser sintering (SLS) and polyjet printing to compare the four 3D printing methods.

Validation of Prototype Method Precision

The precision of the prototype method was validated by comparing the 3D printed models to the original virtual 3D model, using the part comparison analysis tool in 3-matic® Research 10.0 to calculate distances between corresponding surface points [1]. The surface distance data was tested for normality using a Kolmogorov-Smirnov test in SPSS Statistics 22.0 (IMB Corp., Armonk, NY). A Mann-Whitney U test was then performed to determine if there was any statistically significant difference in precision between the 3D printing methods. A two-tailed p-value of <0.05 was considered statistically significant.

The prototype method was further validated by comparing the 3D printed MV models with reference to the SLA model using the same methods.

Validation of Prototype Method Applicability to Cardiac CT and 3D Echocardiography Imaging

The applicability of 3D modelling and printing to different imaging modalities was demonstrated by producing one 3D MV model from cardiac CT imaging data, and another from 3D echocardiography imaging data. The 3D modelling and printing techniques described above for development of the prototype method were followed. Modelling was based on a diastolic phase selected from each data set to clearly demonstrate the anatomical features of the MV and to allow for consistency when comparing the models.

Patient-Specific 3D Printed Models

The prototype method was tested by producing patient-specific 3D printed models for three retrospective MV disease patients—MV prolapse, MV disease associated with an aortic perforation and functional MV pathology. Cardiac CT and 3D echocardiography imaging data was used to produce two models for each patient (one from each imaging modality), to compare 3D printed models produced from different imaging modalities. A patient-specific 3D printed model was also produced using cardiac CT imaging data from a fourth retrospective patient with MV calcification. The model was 3D printed in three different materials to compare rigid, flexible and multi-material 3D prints. The 3D modelling and printing techniques described above for development of the cardiac CT and 3D echocardiography models were followed to produce all patient models. Modelling was based on a particular phase selected from each data set, depending on the patient, in order to clearly demonstrate patient-specific MV pathology.

Cardiac Health Professional Survey

The usefulness of patient-specific 3D MV models in a clinical setting was assessed by surveying cardiac health professionals (CHPs) following their evaluation of the 3D printed models for each patient. A survey tool using a six-point Likert scale was developed, that required each participant to respond to statements regarding the value and potential applications of the 3D printed models.

Results

Prototype Method for MV 3D Modelling and Printing

Virtual and 3D printed MV models produced from CT scans of a plastinated human heart are shown in Figures 1 and 2 respectively. A prototype method for MV 3D modelling and printing was developed and the MV apparatus was virtually reconstructed using the techniques described.

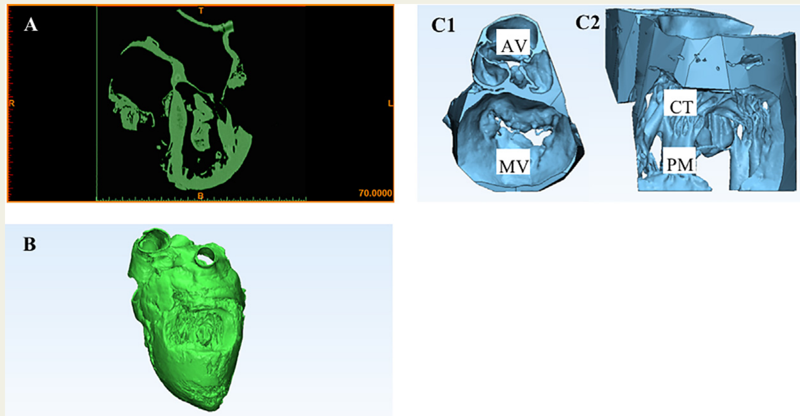

Figure 1 Prototype method for 3D modelling of the MV. CT scans of a plastinated human heart were segmented (A) and a virtual 3D model was calculated (B). The model was then trimmed to isolate the MV apparatus and aortic valve (C). Abbreviations: AV, aortic valve; CT, chordae tendineae; MV, mitral valve; PM, papillary muscle.

Validation of Prototype Method Precision

Colour maps representing the surface distances (mm) between virtual reconstructions of the 3D printed MV models and the original virtual MV model are shown in Figure 3. The MV apparatus was precisely reconstructed using FDM, SLA, SLS and polyjet 3D printing methods. Comparison of the colour maps demonstrated that all 3D printed MV models were produced within submillimetre precision (Table 1, Figure 4). Statistical analysis showed that there was a significant difference ($p < 0.05$) in precision between the models, with the SLA model being the most precise and the polyjet model being the least precise.

Colour maps representing the surface distances (mm) between virtual reconstructions of the 3D printed MV models with reference to the SLA model are shown in Figure 5. The reconstructed FDM (Figure 5A), SLS (Figure 5B) and polyjet (Figure 5C) models were comparable to the reconstructed SLA model within a submillimetre range (Table 2, Figure 6). Statistical analysis showed that there was a significant difference ($p < 0.05$) in similarity between the models, with the SLS model being the most similar (i.e. having the smallest mean surface distance) and the polyjet model being the least similar (i.e. having the largest mean surface distance) to the SLA model. [Results for all other 3D printed MV model comparisons are shown in the supplementary material.]

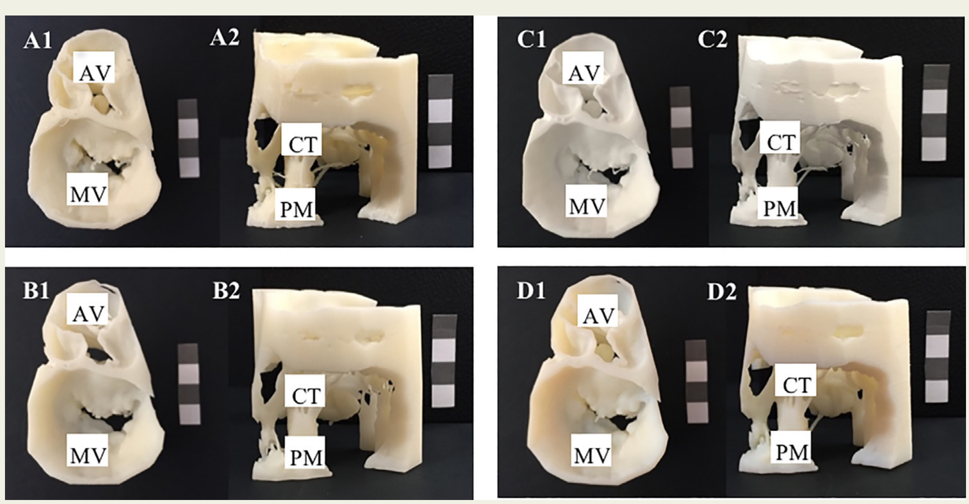

Figure 2 Superior and anterior views of 3D printed MV models. The virtual 3D model of the MV produced from CT scans of a plastinated human heart was 3D printed using fused deposition modelling (A), stereolithography (B), selective laser sintering (C) and polyjet (D) methods.
Abbreviations: AV, aortic valve; CT, chordae tendineae; MV, mitral valve; PM, papillary muscle. [Note: calibration inset, 10 mm x 10 mm squares].

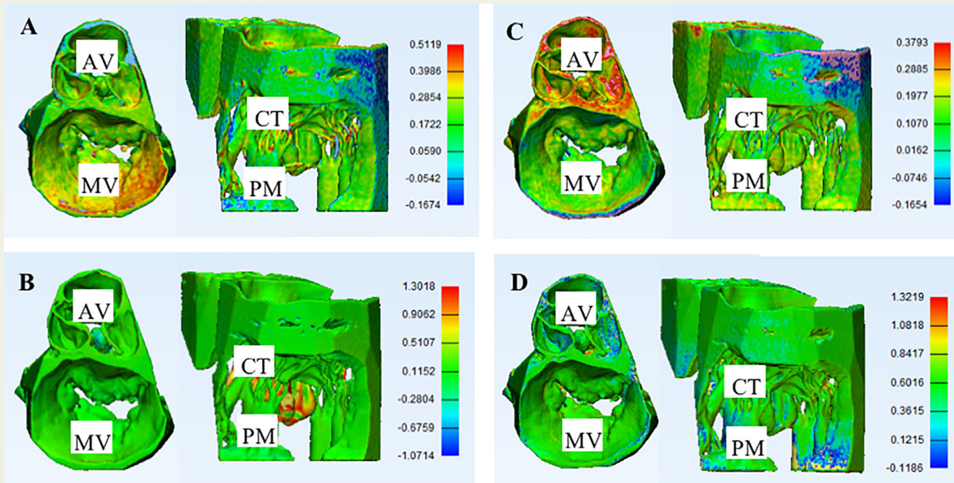

Figure 3 Colour maps representing the surface distances (mm) between virtual reconstructions of 3D printed MV models and the original virtual MV model. The reconstructed FDM (A), SLA (B), SLS (C) and polyjet (D) 3D models were superimposed with the original virtual MV model and surface distances between corresponding surface points were calculated.
Abbreviations: AV, aortic valve; CT, chordae tendineae; MV, mitral valve; PM, papillary muscle; SLA, stereolithographic; SLS, selective laser sintering; FDM, fused deposition modelling.

Validation of Prototype Method Applicability to Cardiac CT and 3D Echocardiography Imaging

Cardiac CT Model

Virtual and 3D printed MV models were produced from cardiac CT imaging data and are shown in Figure 7. The MV leaflets were segmented, although finer structures such as the papillary muscles and chordae tendineae were not fully captured (Figure 7A). This lack of detail was reflected in both the virtual (Figure 7C and D) and 3D printed (Figure 7E) models.

3D Echocardiography Model

Virtual and 3D printed MV models were produced from 3D echocardiography imaging data and are shown in Figure 8. The anterior leaflet was segmented and clearly reconstructed in both the virtual (Figure 8B and C) and 3D printed (Figure 8D) models, although it was difficult to visualise the posterior leaflet. Structures including the papillary muscles and chordae tendineae were not segmented.

Patient-Specific 3D Printed Models

Virtual and 3D printed MV models for patients 1 to 4 are shown in Figures 9–12 respectively. Patient-specific 3D printed models were produced for different MV pathologies from both cardiac CT and 3D echocardiography imaging data. For all patients, there was good correlation between the virtual and 3D printed models as determined by visual inspection. For patients 1 to 3 (Figures 9–11), patient-specific MV anatomy could be visualised from the cardiac CT models, but this was less visible from the 3D echocardiography models. There was good correlation in the anatomy shown by the cardiac CT and 3D echocardiography models for patients 1 and 2 (Figures 9 and 10), although this was less evident for

Table 1 Comparison of the mean surface distance (mm) between virtual reconstructions of 3D printed MV models and the original virtual MV model.

3D printed model	Number of surface points	Minimum surface distance (mm)[a]	Maximum surface distance (mm)	Mean surface distance (mm)	Standard Deviation (mm)
FDM	319940	−1.49	2.68	0.11	0.14
SLA	137575	−3.13	2.87	0.07	0.33
SLS	313333	−0.79	0.95	0.08	0.11
Polyjet	156082	−0.80	3.94	0.25	0.28

Abbreviations: FDM, fused deposition modelling; SLA, stereolithographic; SLS, selective laser sintering; 3D, three dimensional; MV, mitral valve.
[a]Negative distance indicates direction relative to the original virtual MV model.

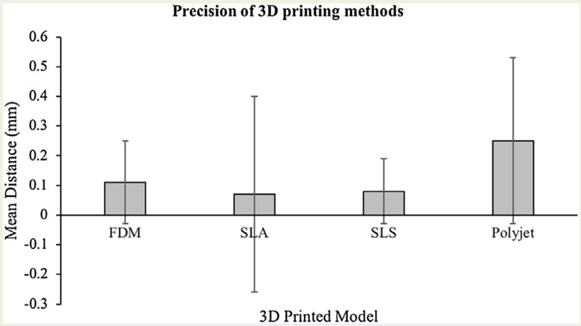

Figure 4 Mean surface distances (mm) between virtual reconstructions of 3D printed MV models and the original virtual MV model. Error bars represent standard deviations for each model.
Abbreviations: 3D, three dimensional; MV, mitral valve.

patient 3 (Figure 11), based on visual inspection. For patient 4 (Figure 12), the calcification could be seen most clearly on the multi-material model (Figure 12D), but was also visible on the rigid model (Figure 12B). The calcification was the least evident on the flexible model (Figure 12C).

Cardiac Health Professional Survey

Forty CHPs, including cardiothoracic surgeons (7.5%), cardiologists (35%), cardiac sonographers (15%), cardiac rehabilitation nurses (5%), advanced trainees (12.5%), anaesthetists (10%), allied health workers (10%) and others (5%), were surveyed. Most respondents agreed that patient-specific 3D printed MV models would be a useful tool in preoperative planning (97.5%), and that they would likely use 3D printed MV models in the future (85%) (Table 3, Figure 13). Examination of patient-specific 3D anatomy, as well as teaching and training, were each indicated by 55% of respondents as potential uses for 3D printed MV models. Surgical planning and simulation of surgical and interventional procedures were also indicated as potential uses by 45% and 42.5% of respondents respectively.

Most respondents agreed that the patient-specific 3D printed MV models provided a different perspective compared to imaging (97.5%), and that the information provided by the models was additional to imaging (90%) (Table 3, Figure 14). There was no clear preference for either the cardiac CT or 3D echocardiography models. A multi-material print was considered the most valuable by 50% of respondents, although the use of a more realistic material was suggested by 42.5% of respondents as a potential improvement to the 3D printed MV models. A higher level of accuracy was suggested by 40% of respondents as another improvement.

Most respondents agreed that they would likely use a virtual 3D model in the future (92.5%) (Table 3, Figure 13). It was also indicated that a virtual 3D model that can be dynamically manipulated would potentially be more useful than a static 3D printed model.

Discussion

This study aimed to assess and validate 3D modelling and printing technology to produce patient-specific 3D MV models. While previous studies have focussed primarily on the feasibility [6,8,9,13,20] and reliability [12,15] of this technology to produce 3D MV models, the current study investigated its precision and quantitatively compared four of the most common 3D printing methods. The study also investigated the applicability of 3D modelling and printing technology to different imaging modalities, specifically cardiac

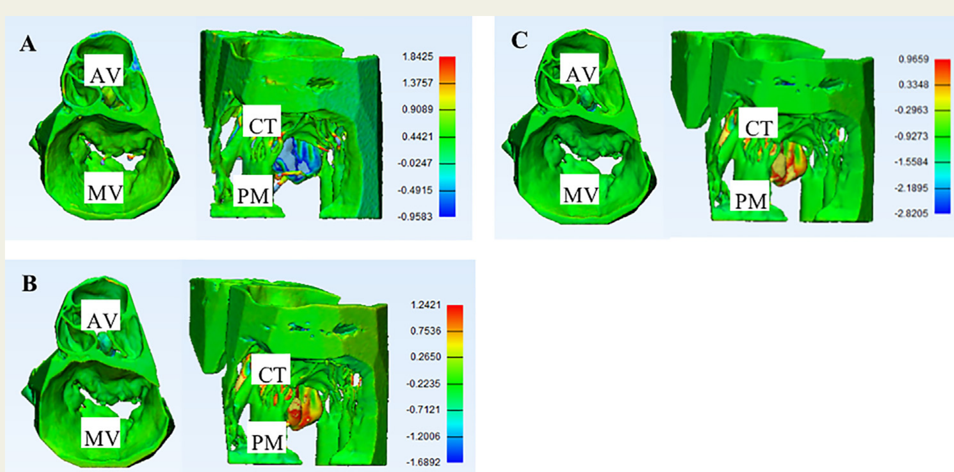

Figure 5 Colour maps representing the surface distances (mm) between virtual reconstructions of 3D printed MV models. The reconstructed SLA model was superimposed with the reconstructed FDM (A), SLS (B) and polyjet (C) models and surface distances between corresponding surface points were calculated.
Abbreviations: AV, aortic valve; CT, chordae tendineae; MV, mitral valve; PM, papillary muscle; SLA, stereolithographic; SLS, selective laser sintering; FDM, fused deposition modelling.

Table 2 Comparison of the mean surface distance (mm) between virtual reconstructions of 3D printed MV models with reference to the SLA model.

3D printed model	Number of surface points	Minimum surface distance (mm)[a]	Maximum surface distance (mm)	Mean surface distance (mm)	Standard Deviation (mm)
FDM	319940	−2.60	3.81	0.08	0.40
SLS	137575	−2.91	3.34	0.05	0.42
Polyjet	137575	−2.04	4.86	0.32	0.63

Abbreviations: FDM, fused deposition modelling; SLA, stereolithographic; SLS, selective laser sintering; 3D, three dimensional; MV, mitral valve.
[a]Negative distance indicates direction relative to the SLA model.

CT and 3D echocardiography. Additionally, the study assessed the value of patient-specific 3D MV models in a clinical setting as perceived by CHPs.

In this study, a prototype method for MV 3D modelling and printing was developed by reconstructing the MV of a plastinated human heart from CT scans. Quantitative analysis of this prototype showed that submillimetre precision was possible using 3D modelling and printing technology. This is consistent with the findings of previous studies showing that plastinated and waxed whole heart specimens could be precisely reconstructed using 3D modelling and printing, based on both qualitative and quantitative analysis [21,22]. These studies, however, focussed only on SLS 3D printing technology. The current study extends beyond these studies to compare FDM, SLA, SLS and polyjet 3D printing technologies and demonstrates that there is a statistically significant difference in precision between these methods. Although significantly different, it should be noted that these differences are only at a submillimetre level and will only be relevant in applications that require this level of precision. Producing patient-specific 3D printed models for medical device sizing, for example, is a potential application where this may be important.

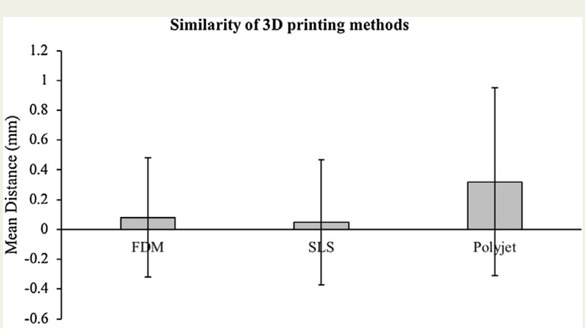

Figure 6 Mean surface distances (mm) between virtual reconstructions of 3D printed MV models with reference to the SLA model. Error bars represent standard deviations for each model.
Abbreviations: 3D, three dimensional; MV, mitral valve; SLA, stereolithographic.

The SLA 3D printed MV model was found to be the most precise based on comparison with the original virtual MV model, followed by the SLS, FDM and polyjet 3D printed models. This was further validated by comparing the virtual reconstructions of the 3D printed models with reference to the SLA model, which showed that the SLS model was the most similar to the SLA model, followed by the SLS, FDM and polyjet models. These findings suggest that if 3D printed models were to be used in a clinical setting, the SLA 3D printing method would be most favoured to produce a model with the highest level of precision.

This study illustrated the applicability of 3D modelling and printing technology to 3D echocardiography as well as cardiac CT imaging data. There is currently limited data on 3D echocardiography-derived 3D printed models of the MV [6,8,9,11]. While this study adds to these findings, further work is warranted to fully investigate the use of 3D echocardiography as a 3D printing image source. This is particularly important given the predominant use of 3D echocardiography to image the MV. Research conducted recently by Vukicevic, Puperi [9] has also compared the use of cardiac CT and 3D echocardiography imaging data to model the MV apparatus. Consistent with the current findings, it was found that both imaging modalities could be used to replicate the MV apparatus, although cardiac CT was superior for replication of subvalvular structures such as the chordae tendineae. While extraction of the chordae morphology from the imaging data was feasible, it presented challenges, which was also revealed in the current investigation. The Vukicevic, Puperi [9] study showed that it was possible to model the subvalvular apparatus from 3D echocardiography using long-axis images, although this was not sufficient to fully replicate the chordae tendineae. Only en-face images were used in the current study, so only the MV leaflets could be modelled.

In the survey of perceptions of the patient-specific 3D printed models produced, most respondents agreed that 3D printed models would be a useful tool in preoperative planning. This compared favourably with a similar study conducted by [23], which found that clinicians considered 3D printed models useful for surgical planning in patients with pulmonary atresia. In the field of cardiology, however, the primary focus of the use of patient-specific 3D printed

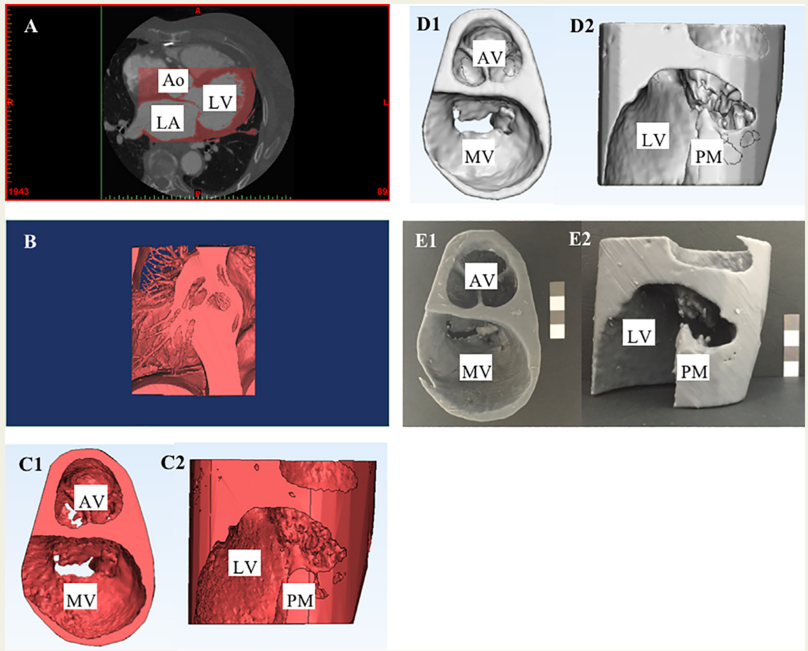

Figure 7 3D MV model produced from cardiac CT imaging data. Cardiac CT scans were segmented (A) and a virtual 3D model was calculated (B). The model was trimmed to isolate the MV apparatus, left ventricular cavity and aortic valve (C) and refined through anatomical engineering (D). The model was then 3D printed using stereolithography (E). Abbreviations: 3D, three dimensional; MV, mitral valve; Ao, aorta; AV, aortic valve; LA, left atrium; LV, left ventricle; MV, mitral valve, PM, papillary muscle. [Note: calibration inset, 10 mm x 10 mm squares].

models to date has been in cases of vascular and whole heart pathologies [23–38]. While there have been studies conducted to investigate the application of this technology to the planning of valvular procedures [5,7,9,10,39–41], this data is very limited. The current study focusses specifically on patient-specific 3D models of the MV, which is complex and therefore challenging for clinicians to address. It is here that 3D printed models could be a valuable tool to assist in overcoming these challenges.

Although all the 3D printed models presented were considered valuable, the multi-material print, combining both flexible and rigid materials, was preferred by 50% of CHPs surveyed. One CHP indicated that the use of multiple materials allowed for more information regarding pathologies

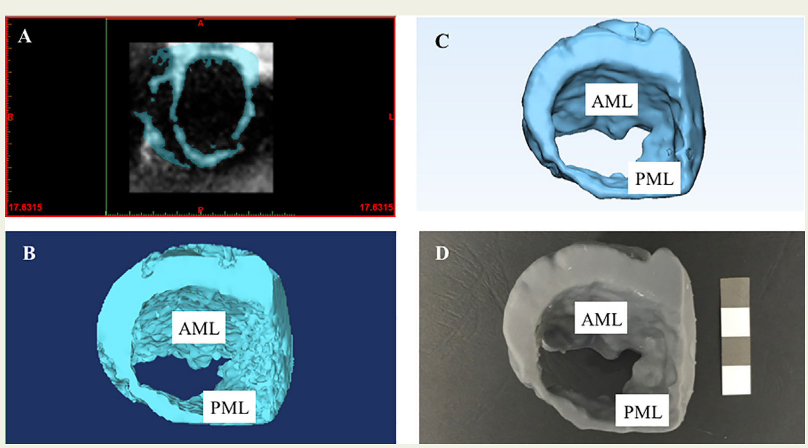

Figure 8 3D MV model produced from 3D echocardiography. Imaging data was segmented (A) and a virtual 3D model was calculated (B). The model was refined through anatomical engineering (C) and then 3D printed using stereolithography (D). Abbreviations: 3D, three dimensional; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet. [Note: calibration inset, 10 mm x 10 mm squares].

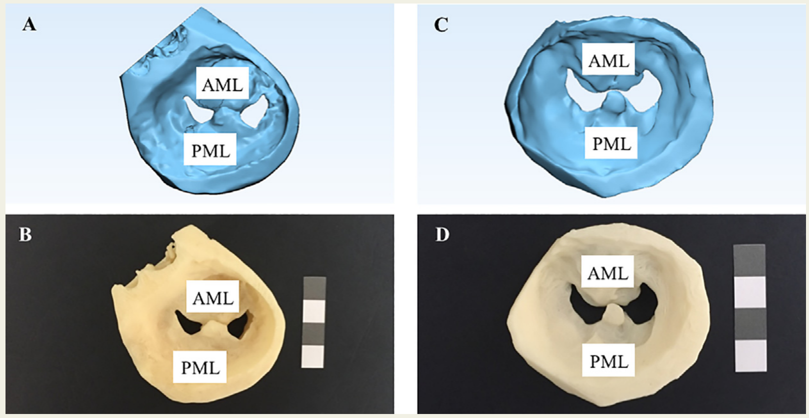

Figure 9 Virtual and 3D printed MV models for patient 1 with MV prolapse. Cardiac CT and 3D echocardiography imaging data was used to produce virtual 3D models (A and C respectively), which were 3D printed using fused deposition modelling (B and D respectively) to compare 3D printed models produced from different imaging modalities.
Abbreviations: 3D, three dimensional; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet. [Note: calibration inset, 10 mm x 10 mm squares].

such as calcification, to be gathered from the 3D printed model. This preference may also be due to the relatively close resemblance of the flexible material to the properties of the MV compared to rigid materials. Therefore, such a model could be manipulated to simulate the potential effects of surgical or interventional procedures, which may not be as feasible using a rigid model. It has previously been shown that a dual-material 3D print using flexible materials with different properties could be used to replicate MV leaflet properties [9]. This was achieved to a sufficient degree to allow for the interaction of catheter-based MV repair devices with the leaflets to be modelled. However, the exact replication of specific MV tissue properties and complex pathologies requires further investigation.

Study Limitations

Although the current study demonstrated how 3D modelling and printing technology can be used to illustrate a range of MV disease pathologies, and that both cardiac CT and 3D echocardiography imaging data can be used to produce patient-specific 3D MV models, this analysis was qualitative and was not validated using quantitative methods. While the prototype developed was also applied to patient-specific cases, 3D printed models were produced for a small patient

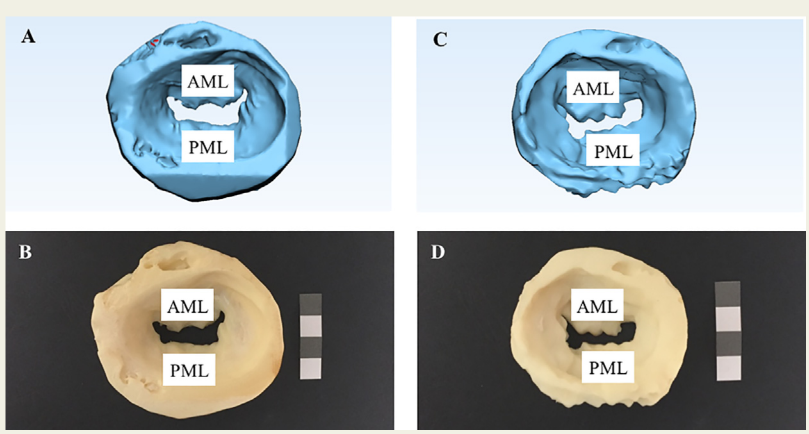

Figure 10 Virtual and 3D printed MV models for patient 2 with MV disease associated with an aortic perforation. Cardiac CT and 3D echocardiography imaging data was used to produce virtual 3D models (A and C respectively), which were 3D printed using fused deposition modelling (B and D respectively) to compare 3D printed models produced from different imaging modalities.
Abbreviations: 3D, three dimensional; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet. [Note: calibration inset, 10 mm x 10 mm squares].

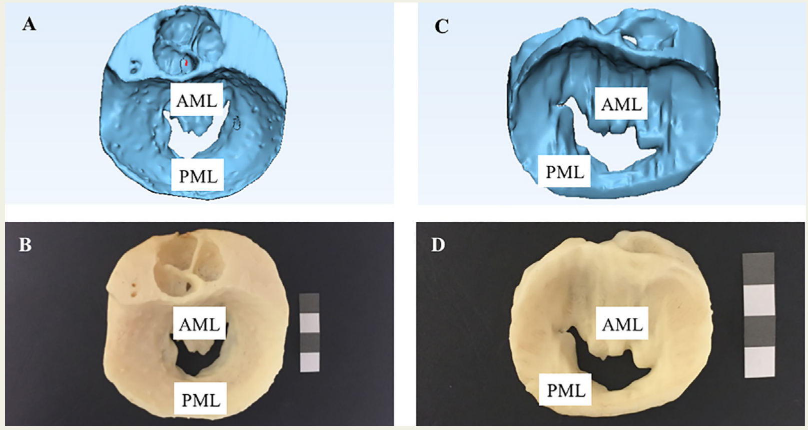

Figure 11 Virtual and 3D printed MV models for patient 3 with functional MV disease. Cardiac CT and 3D echocardiography imaging data was used to produce virtual 3D models (A and C respectively), which were 3D printed using fused deposition modelling (B and D respectively) to compare 3D printed models produced from different imaging modalities.
Abbreviations: 3D, three dimensional; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet. [Note: calibration inset, 10 mm x 10 mm squares].

cohort. However, perceptions of these models were collected from a wide range of CHPs who may benefit from their use in patient management.

It is important to acknowledge that although useful, 3D modelling and printing technology itself also has limitations, which have been discussed in the literature [1]. These inherent limitations of 3D modelling and printing technology may explain the suggestions for improvement of the 3D printed models made by the CHPs surveyed, which were predominantly focussed around precision.

Future Directions

In light of the current study, further work should aim to quantitatively compare the precision of 3D models produced from different imaging modalities. While the study also provided a useful insight into CHP perceptions of 3D printed models, gathering perceptions from a larger number of surgeons who would potentially utilise them for preoperative planning would add value to the results. The findings could also be built upon by further prospective studies assessing the impact of the use of patient-specific 3D models on patient

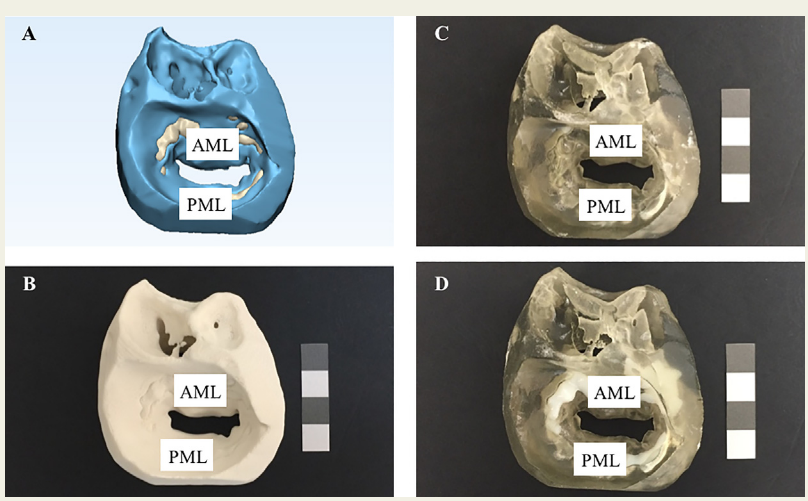

Figure 12 Virtual and 3D printed MV models for patient 4 with MV calcification. Cardiac CT imaging data was used to produce a virtual 3D model (A), which was 3D printed in three different materials to compare rigid (B), flexible (C) and multi-material (D) 3D prints.
Abbreviations: 3D, three dimensional; MV, mitral valve; AML, anterior mitral leaflet; PML, posterior mitral leaflet. [Note: calibration inset, 10 mm x 10 mm squares].

Table 3 Cardiac health professionals' perceptions of patient-specific 3D MV models (n = 40).

Statement	Frequency of responses (%)						
	Strongly disagree	Disagree	Slightly disagree	Slightly agree	Agree	Strongly agree	Average Likert scale score[a]
The 3D printed model is a useful tool for preoperative planning	–	–	2.5	22.5	55	20	4.9
The 3D printed model provides a different perspective to imaging	–	–	2.5	17.5	52.5	27.5	5.1
The information provided by the 3D printed model is additional to that provided by imaging	–	2.5	7.5	30	32.5	27.5	4.8
I am likely to use a 3D printed model for preoperative planning in the future	–	5	10	37.5	22.5	25	4.5
I would use a virtual 3D model for preoperative planning	–	5	2.5	37.5	27.5	27.5	4.7
The 3D printed model was an accurate representation of the patient-specific anatomy (for patient clinicians only[b])	–	–	40	40	20	–	3.8

Abbreviation: 3D, three dimensional.

[a]1 = strongly disagree; 2 = disagree; 3 = slightly disagree; 4 = slightly agree; 5 = agree; 6 = strongly agree.

[b]Number of patient clinicians surveyed = 5.

outcomes, which most of the research conducted to date in this area has not addressed.

The medical applications of 3D modelling and printing can also be extended beyond preoperative planning, and these have been reviewed in the literature [1,42–47]. Patient-specific prosthesis development, tissue engineering, medical education and patient-clinician interactions are some notable areas where further research into the use of this technology could be relevant. Three dimensional printed patient-specific prostheses have already been utilised in fields such as orthopaedics [48,49], and this could be expanded into cardiovascular medicine to produce replacement heart valves more rapidly and with higher precision than current methods. An extension of this would be the fabrication of tissue-engineered heart valves that replicate cardiovascular tissue, as well as other tissues in the body. This could potentially lead to the fabrication of entire organs for transplants, which may overcome donor shortages. 3D modelling and printing may also address the issue of limited access to cadaveric material for medical education, as well as provide an alternative to these resources without the associated practicality, health and safety, and ethical issues. In a clinical setting, patients may also receive an educational benefit from the use of 3D printed models, as these could be utilised by clinicians to illustrate pathologies, surgical procedures and treatment options. As patient trust in these tools increases, this may enhance patient-clinician interactions such as obtaining informed consent in the future.

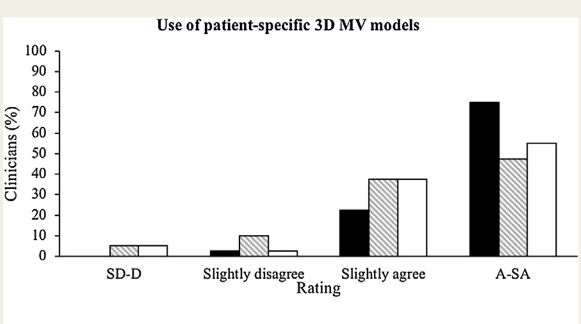

Figure 13 Cardiac health professionals' perceptions of patient-specific 3D MV models (n = 40). A, agree; D, disagree; SA, strongly agree; SD, strongly disagree.

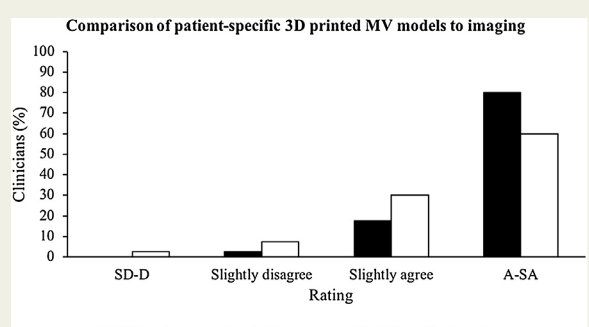

Figure 14 Cardiac health professionals' perceptions of patient-specific 3D printed MV models compared to imaging (n = 40). A, agree; D, disagree; SA, strongly agree; SD, strongly disagree.

Conclusions

This study investigates the application of 3D modelling and printing technology in the context of the MV. The results of this study suggest that, with further advances in 3D modelling and printing, patient-specific 3D MV models could serve as a useful clinical tool, with the potential to benefit both patients and health professionals in the future. The findings also highlight the potential of this technology to be applied in a variety of medical areas beyond preoperative planning, within both clinical and educational settings.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.hlc.2017.10.017.

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