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Preoperative planning with three-dimensional reconstruction of patient's anatomy, rapid prototyping and simulation for endoscopic mitral valve repair

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Abstract

OBJECTIVES: Mitral valve repair performed by an experienced surgeon is superior to mitral valve replacement for degenerative mitral valve disease; however, many surgeons are still deterred from adapting this procedure because of a steep learning curve. Simulation-based training and planning could improve the surgical performance and reduce the learning curve. The aim of this study was to develop a patient-specific simulation for mitral valve repair and provide a proof of concept of personalized medicine in a patient prospectively planned for mitral valve surgery.

METHODS: A 65-year old male with severe symptomatic mitral valve regurgitation was referred to our mitral valve heart team. On the basis of three-dimensional (3D) transoesophageal echocardiography and computed tomography, 3D reconstructions of the patient's anatomy were constructed. By navigating through these reconstructions, the repair options and surgical access were chosen (minimally invasive repair). Using rapid prototyping and negative mould fabrication, we developed a process to cast a patient-specific mitral valve silicone replica for preoperative repair in a high-fidelity simulator.

RESULTS: Mitral valve and negative mould were printed in systole to capture the pathology when the valve closes. A patient-specific mitral valve silicone replica was casted and mounted in the simulator. All repair techniques could be performed in the simulator to choose the best repair strategy. As the valve was printed in systole, no special testing other than adjusting the coaptation area was required. Subsequently, the patient was operated, mitral valve pathology was validated and repair was successfully done as in the simulation.

CONCLUSIONS: The patient-specific simulation and planning could be applied for surgical training, starting the (minimally invasive) mitral valve repair programme, planning of complex cases and the evaluation of new interventional techniques. The personalized medicine could be a possible pathway towards enhancing reproducibility, patient's safety and effectiveness of a complex surgical procedure.

Keywords: Mitral valve repair • Simulation • Minimally invasive • Rapid prototyping • Preoperative planning

INTRODUCTION

It has been well established that mitral valve repair is desirable and superior to replacement for degenerative mitral valve pathology [1, 2]. However, many surgeons are still deterred from adapting this procedure because of the steep learning curve. Indeed, there are multiple repair techniques a surgeon can choose from to address the mitral valve pathology. Consequently, the success of the repair is predominantly a reflection of the surgeon's skills and experience.

This is best demonstrated by Bolling *et al*., utilizing the Society of Thoracic Surgeon database of patients undergoing mitral valve surgery in the USA. The mean repair rate was 41%, and the median number of operations per surgeon was 5 cases per year. In this study, increased surgeon-level volume was independently associated with an increased probability of mitral repair [3].

The association of procedural volume and outcome has been demonstrated for many complex procedures, including mitral valve surgery [3–6]. Consequently, mitral valve repair has been concentrated around individual surgeons with a strong track record rather than being a reproducible procedure in the hands of any cardiac surgeon [3, 7]. For minimally invasive mitral valve repair, the situation is even more complicated, as the typical number of operations to overcome the learning curve is between 75 and 125 cases [8].

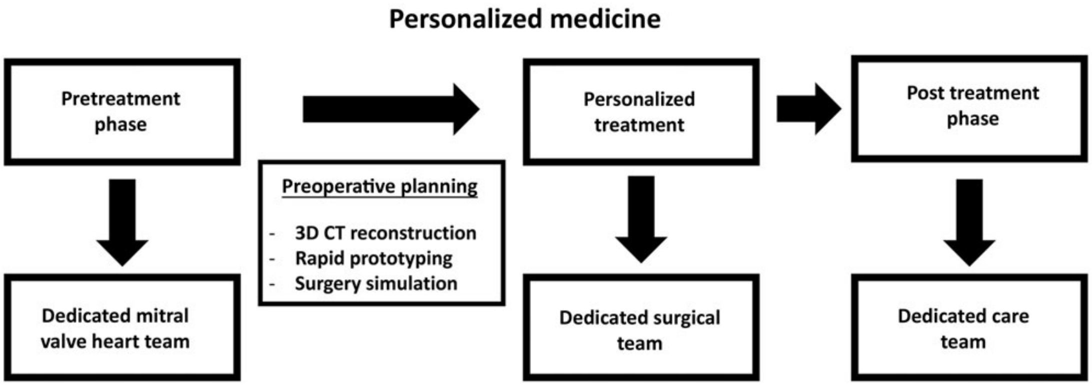

Figure 1: Concept of personalized medicine. 3D: three-dimensional; CT: computed tomography.

Simulation-based training and preoperative planning could enhance the effectiveness, reproducibility and safety of the mitral valve repair. Indeed, prospective randomized studies in general surgery have shown that simulation-based training improves surgical performance and reduces intraoperative errors significantly [9–11]. For a complex procedure, such as mitral valve repair, it is even more pertinent to introduce simulation-based training and planning.

The aim of this study was to develop a patient-specific simulation for mitral valve repair and provide a proof of concept of personalized medicine (Fig. 1) in a patient prospectively planned for mitral valve surgery.

METHODOLOGY

Evaluation by mitral valve heart team

The patient was a 64-year old male referred to the mitral valve heart team (two imaging cardiologists, two interventional cardiologists and one cardiothoracic surgeon, all with expertise on mitral valve pathology) at our institute. The patient had no medical history and was in dyspnoea NYHA Class III at referral. A transthoracic echocardiography showed a left ventricular ejection fraction of 68%, left ventricle diastolic diameter of 52 mm, left ventricle systolic diameter of 32 mm and severe mitral regurgitation with an effective regurgitant orifice of 0.53 cm^2. The mechanism of regurgitation was prolapse of the P2 segment of the posterior leaflet. The patient had a coronary angiogram in 2012 that showed no flow limiting lesions with a dominant right coronary artery. We decided to perform a three-dimensional (3D) transoesophageal echocardiography (TOE) and a coronary computed tomography (CT), combined with CT of the entire aorta with ilio-femoral vessels, to evaluate the suitability for endoscopic port-access mitral valve repair as described before [12]. The institutional review board of Maastricht University Medical Centre approved the multidimensional modelling and simulation for preoperative planning.

Computed tomography scan and three-dimensional reconstruction

The patient underwent an ECG-gated multidetector CT (Somatom Definition Flash, Siemens, Forchheim, Germany) of the heart and the complete aorta. Furthermore, a high-pitch CT angiography of the peripheral arteries was performed after intravenous administration of 75 cc Iopromide 300 mg I/ml (Ultravist 300, Bayer, Berlin, Germany).

CT scan did not show any significant coronary disease. Using the C-station and Vesalius3D software (PS-medtech, Amsterdam, Netherlands), two-dimensional CT data were used to acquire a 3D reconstruction model as described before [12]. On the basis of this 3D reconstruction, we could determine that the ilio-femoral vessels and the aorta were suitable for port-access approach [12]. Additionally, we could determine the ideal position for the chest incision (Video 1).

Video 1: (**1.1**) Assessment of anatomical eligibility for minimally invasive mitral valve surgery: peripheral access, intercostal incision height. (**1.2**) Assessment of specific mitral valve pathology: P2 prolapse during the heart cycle and in systole and conversion to stereolithography file.

Three-dimensional reconstruction of mitral valve

The images were obtained, using a Philips iE33 with a 3D TOE probe (Philips Medical Systems, Andover, MA, USA), throughout the entire cardiac cycle. The images were cropped at the border of the left side of the heart using QLab 9.1 (Philips Medical Systems).

The TOE images were imported into Vesalius3D software and converted to a full dynamically 3D reconstructed left-side heart image. The 3D reconstructed model could then be cropped at any level using the C-station. This dynamic model could then be stopped at any step of the cardiac cycle (Video 1). The images were converted into stereolithography file for rapid prototyping (Fig. 2A).

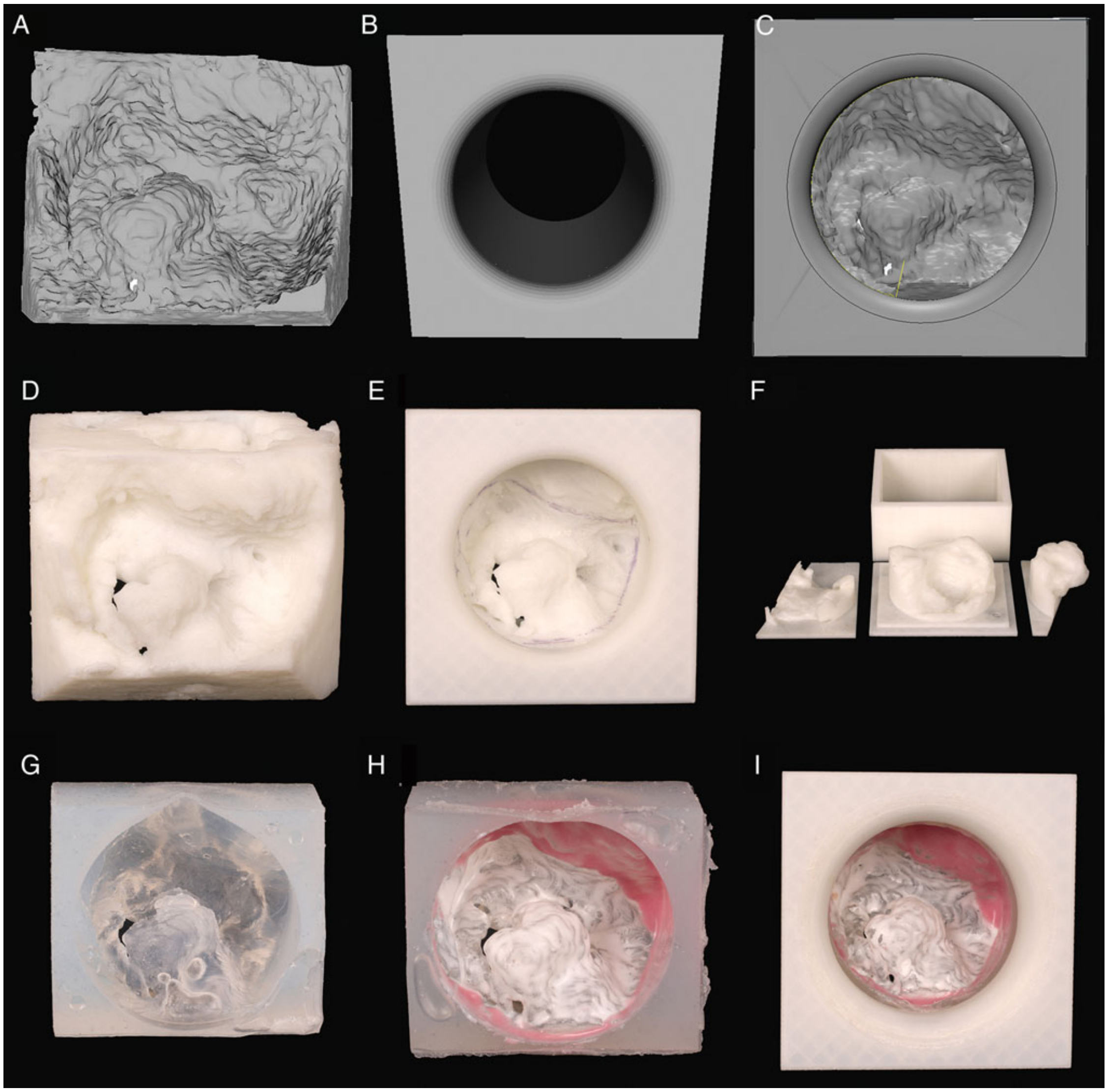

Figure 2: (**A**) Stereolithography model for rapid prototyping, (**B**) simulator template, (**C**) valve model in virtual cylinder, (**D**) original rigid rapid prototype, (**E**) rigid rapid prototype in simulator template, (**F**) negative mould, (**G**) casted silicone replica, (**H**) coloured silicone replica and (**I**) silicone replica fitted in simulator template.

Rapid prototyping and casting of patient-specific silicone replica

We chose to print the mitral valve in systole to evaluate the prolapse more adequately. First, we manufactured the raw mesh in Acrylonitrile Butadiene Styrene (ABS) without any pre-processing. To fit this model into the simulator template (Fig. 2B), the mesh was converted into a two-dimensional (2D) form, preserving the valve only, by placing a virtual cylinder over the mesh and performing a Boolean intersect operation, using 3-MATIC (Materialise, Leuven, Belgium) (Fig. 2C).

The material chosen was special silicone to allow manipulation in the simulator. However, rapid prototyping in silicone is not available. Therefore, we designed a process of negative mould fabrication and silicone casting. Because of overhangs and bridges, a three-part mould was designed to be able to remove the silicone following solidification (Fig. 2D–F). Subsequently, the silicone was coloured for distinguishing the leaflets from atrium and was fitted into the simulator template (Fig. 2G–I).

Preoperative repair of mitral valve in the simulator

The patient-specific silicone was inserted into the high-fidelity mitral valve simulator that has been developed at our institute. The simulator can be used for the simulation of port-access mitral valve surgery by endoscopic techniques, by robotic assistance and for conventional mitral valve surgery. The mitral valve component is disposable and is developed from special silicone that mimics the tissue characteristics of the mitral valve so that a true suturing experience can be created. The simulator uses also a metric-feedback system, regarding the exact depth and length of each suture. The depth and length of each suture attempts can be pre-set, and the simulator will provide scoring about the suture attempts with regard to pre-set values.

On the basis of the preoperative planning, there was an isolated prolapse of P2 based on chordae elongation (length 46 mm). The P2 segment was tall and wide, whereas all other segments of the mitral valve were normal. All repair techniques could be tried out on the simulator. A full resection of this diseased area would be less desirable as not enough remaining tissue would be available

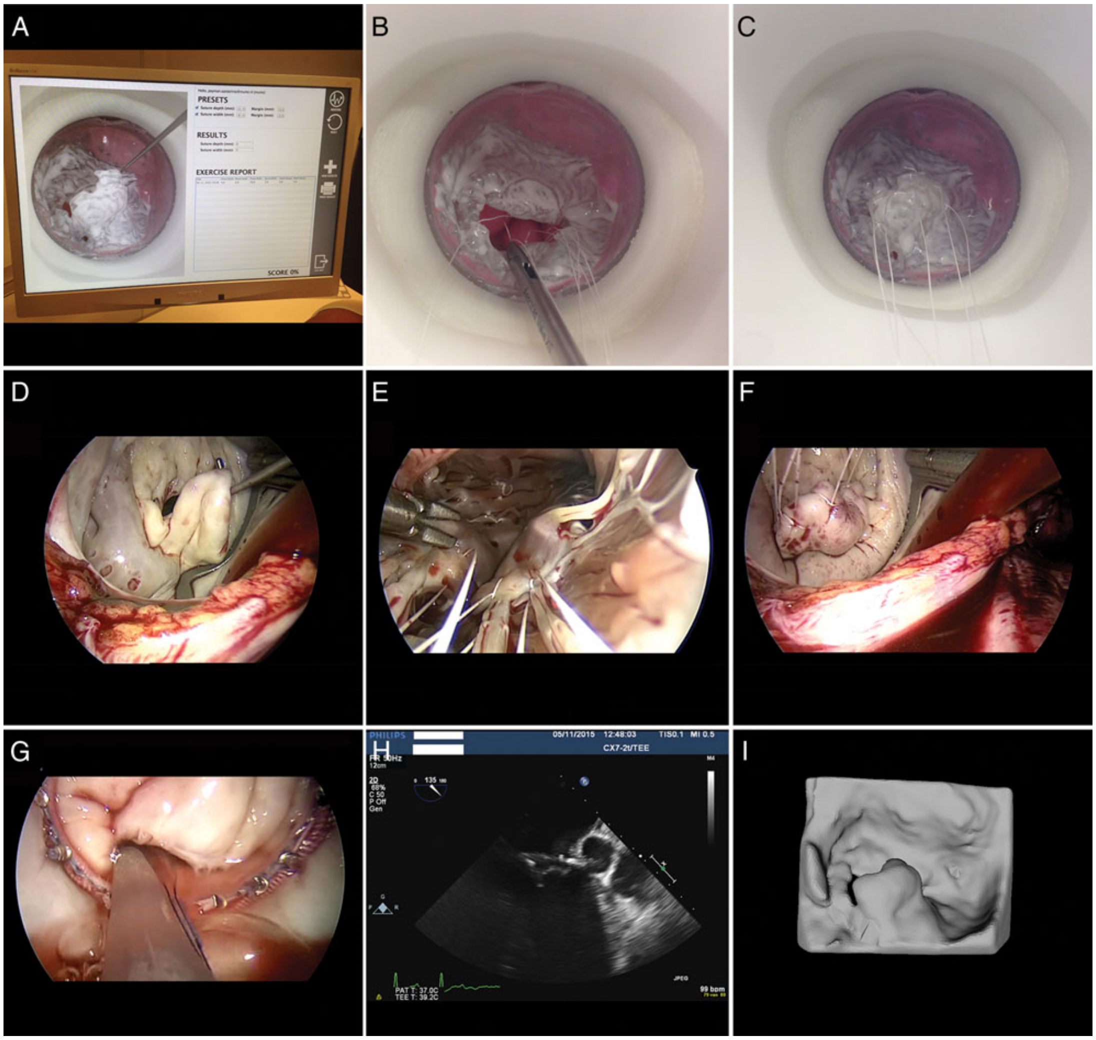

Figure 3: (**A**) Evaluating the P2 prolapse in the simulator, (**B**) simulation of neochords placement on papillary muscles, (**C**) simulation of prolapse correction, (**D**) intraoperative evaluation of P2 prolapse, (**E**) intraoperative neochords placement on papillary muscles, (**F**) intraoperative prolapse correction, (**G**) intraoperative pseudo-prolapse of the anterior leaflet during the saline test, (**H**) postoperative echocardiographic coaptation length and (**I**) post-processing of stereolithography model.

Video 2: (**2.1**) Intraoperative testing of mitral valve pathology. (**2.2**) Intraoperative correction of P2 prolapse. (**2.3**) Pseudo-prolapse of the anterior mitral valve leaflet after correction of P2 prolapse. (**2.4**) Postoperative echocardiographic results.

to reconstruct the posterior leaflet. Therefore, we chose to use three pairs of neochords to bring the prolapsed area down into the left ventricle (Fig. 3A–C). On the basis of the measurements of the anterior leaflet (31 mm), annulus (anteroposterior diameter of 41 mm) and P2 segment (30 mm tall), we chose to oversize and use a 34 mm annuloplasty ring [avoiding systolic anterior motion (SAM)]. The length of the neochords was based on overcorrecting the prolapse (avoiding SAM) and to have a coaptation length of ≥8 mm. After the annuloplasty ring placement, a small fold was created in the middle of the P2 (because of a wide P2) that was closed to create a smooth posterior leaflet for coaptation. As the valve was printed in systole, no special testing was required than adjusting the coaptation length.

RESULTS

Operation

A right-sided port-access incision of 4 cm was made in the fifth intercostal space. Visualization was accomplished by a 5 mm endoscope, and the cardiopulmonary bypass was established by cannulation of the right femoral artery and vein as described before [12]. The mitral valve was approached through the left atrium and was assessed by the use of nerve hooks. There was an isolated prolapse of P2 based on chordae elongation (Fig. 3D; Video 2). The mitral valve pathology was exactly the same as on preoperative planning. The mitral valve repair was done as in simulation by the placement of three pairs of neochords on P2, placement of annuloplasty ring of 34 mm and closing of the fold of P2 (Fig. 3E and F; Video 2).

After valve repair, the left ventricle was filled with saline to test the final result. Unfortunately, an unexpected event occurred: the full anterior leaflet was now prolapsing (Fig. 3G; Video 2). Despite the additional manoeuvres—pushing the diaphragm down, lowering the atrial retractor and pushing on the annuloplasty ring anteriorly—evaluating the final result with saline test was impossible. The prolapse of the anterior leaflet was not present on preoperative TOE or 3D printed valve. We considered this to be a pseudo-prolapse caused by displacement of the papillary muscles in the resting heart of normal size. This is a rare phenomenon that can falsely urge an inexperienced mitral valve surgeon to repair the anterior leaflet. We decided to evaluate the final result on intraoperative TOE. The intraoperative TOE showed no prolapse of any segments of the valve, a low gradient and coaptation of >8mm (Fig. 3H).

Image processing after validation

We used raw TOE data for rapid prototyping, because we did not want to manipulate the diagnostic images before validating the process. However, raw TOE data result in a prototype, possessing rough surfaces, non-mesh holes (i.e. signal loss) and unwanted structures (i.e. noise). However, with processing of the data with MeshLab freeware (MeshLab Version 1.3.3, Visual Computing Lab—ISTI—CNR), we are able to eliminate these artefacts based on an automated algorithm (Fig. 3I).

Postoperative course and echo

The postoperative course was uneventful, and the patient was discharged home on the 5th postoperative day. The transthoracic echocardiography on discharge showed a trace of MR and a mean gradient of 4 mmHg and good left ventricular function (Video 2).

DISCUSSION

We have developed a patient-specific simulation for mitral valve repair and provided a proof of concept of personalized medicine in a patient prospectively planned for surgery. Our patient was discussed by a dedicated mitral valve heart team, and surgical access was chosen based on the patient's anatomy. For the mitral valve repair, we casted a patient-specific mitral valve silicone replica for preoperative evaluation of repair options in a high-fidelity simulator. The patient was then operated accordingly by a dedicated mitral valve surgeon and operating team.

We anticipate that patient-specific simulation could enhance the reproducibility, patient's safety and effectiveness of mitral valve repair in the hands of many more surgeons. Additionally, this concept will help to train surgeons and overcome their learning curves more easily as demonstrated for other surgical procedures [9–11].

With the emergence of a variety of minimally invasive procedures, the focus is shifting from whether a minimally invasive procedure is superior to conventional treatment to the question: Which patient is more suitable for which technique? This question can be answered by preoperative planning whereby the individual patient's anatomy, together with conventional parameters, is taken into consideration for decision-making in a multidisciplinary fashion.

We have recently shown that preoperative planning with 3D CT reconstruction models is useful and feasible to determine the operative strategy and exclude patients ineligible for a minimally invasive approach. In addition, with the advent of many transcatheter mitral valve repair systems, patient-specific mitral valve models could guide us to choose the best surgical repair option [12].

Unfortunately, we could not print the mitral valve in silicone. Therefore, we had to develop a process of negative mould fabrication and silicone casting to create the patient-specific silicone replica. We applied the same process and developed additional four different patient-specific pathological moulds. These moulds can subsequently be used to manufacture different pathology-specific silicone replica in mass for educational purposes. We anticipate that in the future, 3D printing in silicone could be commercially available, simplifying the process.

We have previously shown that by processing the 3D TOE images by open source software, we could provide even more accurate 3D image of the mitral valve. This process is time-consuming, operator-dependent and is not validated yet [13]. Therefore, we used raw TOE data to evaluate whether it would be feasible to use TOE as the basis for rapid prototyping, making it more applicable.

One of the challenges in mitral valve surgery is testing the valve on the arrested heart. The commonly used saline test of the mitral valve in an arrested heart does not accurately reflect its function in a beating heart. The assessment of the valve may differ from the preoperative and postoperative echocardiographic findings [14]. We unexpectedly had a prolapse of the anterior leaflet during the saline test that was not present on preoperative planning. Although the mitral valve pathology was a simple one, an inexperienced surgeon could have been easily urged into correcting this prolapse and ending up with an unsatisfactory result. We chose to rely on preoperative planning and found no prolapse in the postoperative echo.

We chose to print the mitral valve in systole to evaluate the prolapse more adequately. By printing the valve in systole, no special testing was required other than correcting the mal-coaptation area. This technique might provide more reproducibility of performing the repair without relying on the saline test on an arrested heart.

The P2 prolapse is one of the easiest and most prevalent pathologies of patients scheduled for mitral valve surgery, and still the overall repair rate of mitral valve is low. Therefore, we used this valve pathology for the proof of concept; however, we are able to apply this concept to most complex pathologies in preoperative planning.

We recognize that experienced mitral valve surgeons would not necessarily need the tools that have been provided here for simple mitral valve pathologies. However, the concept provided is meant to make the procedure reproducible in the hands of less experienced surgeons, to make training of the surgeons easier and to move from trial and error to new era of surgery where reproducibility, safety and effectiveness are maximized.

Other groups have developed low-fidelity mitral valve repair simulators and have shown that simulation-based learning with formative feedback results in improved surgical performance [15–17]. In addition to this, there are also groups working on computational modelling of mitral valve with repair options [18, 19]. However, this is the first report of simulation with patient-specific mitral valve in which a surgeon can evaluate the repair options, plan complex cases and develop repair's skills through different surgical access.

We have provided a proof of concept of personalized medicine for mitral valve repair as a possible pathway to make a complex procedure more reproducible, more effective and safer in the hands of many more surgeons. Further research is necessary to test whether the premises of this concept will hold.

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Conflict of interest: none declared.

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