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NEW IDEAS

A novel low-fidelity simulator for both mitral valve and tricuspid valve surgery: the surgical skills trainer for classic open- and minimally invasive techniques†

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Abstract

OBJECTIVES: Simulators have been proven to equip trainee surgeons with better skills than the traditional, standard approach to skill development. The purpose of this study was to develop a low-fidelity, low-cost, reusable and portable simulation device, which could provide training in nearly the full range of mitral valve surgery techniques, in both the classic, open approach as well as the minimally invasive approach.

METHODS: This novel simulator is made up of commonly available components. The basic elements are a classic baby bottle, with the associated feeding teat and screw ring, in combination with a sheet of dental dam. The detailed process for making this simulator is outlined in this article. Maximum suture tensile strength on the different components was tested with a digital force gauge. Reusability and the rate of wear as a result of suturing were documented. Total cost was calculated in euros (€).

RESULTS: This study resulted in a simulation model very similar in size to the actual anatomical dimensions of the mitral valve. Various pathological conditions, according to Carpentier's Functional Classification, could be simulated. This led to the possibility of providing training in several mitral valve surgical techniques. As the model developed, it became clear that it could also be used to practice tricuspid valve surgery techniques. Maximum mean suture tensions on the silicone teat and dental dam were 42.11 and 11.15 N/m^2, respectively. The feeding teat started wearing after approximately 45 suture placements. Total cost of the study model was €5.14.

CONCLUSIONS: This relatively simple, low-cost, low-fidelity model can provide simulation training in nearly the full range of mitral valve and tricuspid valve surgical techniques, in both the classic open approach and the minimally invasive approach—and do so almost anywhere. Especially when used by young cardiothoracic surgeons in training, this model may contribute to the development of technical skills and procedural knowledge required for adequate performance in the operating room.

Keywords: Education • Simulation • Surgical skills • Mitral valve • Tricuspid valve • Minimally invasive technique

INTRODUCTION

Compared with traditional approaches to skill development, the use of simulators has been proven to equip trainees with better skills in general surgery [1, 2].

In recent years, there has been increasing emphasis on skills and simulation training for trainees in cardiothoracic surgery, a branch in which exposure to surgical procedures appears to be declining. Perhaps this is most apparent in the reduction of exposure to mitral valve surgery [3]. Reasons for this are, firstly, that modernisation of the trainee curriculum places emphasis on other skills, of a personal nature, rather than focussing on training in technical skills [4]. Secondly, an increasing number of mitral valve procedures are performed by minimally invasive surgery. Nowadays, even fewer complex procedures are performed by experienced surgeons to gain familiarity with the minimally invasive approach. In the near future, the training of residents in mitral valve surgery will possibly shift more to programmes outside the operating theatre.

To the best of our knowledge, the only low-fidelity simulator currently on the market is an expensive, single-use plastic mitral valve model made by the Chamberlain Group (Great Barrington, MA, USA [5]. In the Chamberlain model, only one specific aspect of mitral valve repair can be simulated. High-fidelity simulators are scarce and not really designed for instruction in mitral valve surgery [6]. Currently, most simulation training is performed on bovine or porcine heart models [3, 7]. Even so, special instruments have been designed in response to the need to make mitral valve training 'at home', with animal hearts, a simpler matter [8].

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The purpose of this study was to develop a low-fidelity, low-cost, reusable and portable simulator, on which training in nearly the full range of mitral valve surgical techniques—in both the classic open- and minimally invasive approaches—could be provided in any conceivable location.

METHODS

The basic components of the simulator comprise a classic baby bottle (Philips Avent, Eindhoven, NL) with the associated feeding teat and screw ring. The bottle itself is used as a holder for the simulated mitral valve structures and also functions as a storage container (Fig. 1). The different tiers of the feeding teat—manufactured from 0% bisphenol-A silicone—represent the annulus and the subvalvular apparatus. The teat was extensively tested for maximum suture tension, using a digital force gauge and the wear process, caused by repeated suturing with 2-0 Ti-Cron (Covidien, Mansfield, MA, USA), was documented. The lower base of the teat consists of two flanged silicone rings. The teat was customized by cutting the two flanges to ensure good fixation in the screw ring. The inner silicone ring simulates the annulus of the mitral valve. The outer diameter of this ring is 40 mm and the inner diameter is 30 mm (Fig. 2). The final width of the simulated annulus is 5 mm around the entire circumference. Thickness of the simulated annulus is 3 mm. Lengthwise, the teat can be divided into a wider base and a smaller tip. The teat was cut in half and incised horizontally in both ways at the bottom of the base, a few millimetres above the silicone ring. By making this 2 mm horizontal incision at the base, the two halves could be placed slightly apart. These two halves represent the subvalvular apparatus. The transition between the wider base and the smaller tip simulates the attachment of chordae on both the anterolateral- and posteromedial papillary muscle groups (Fig. 3). The length of the simulated chordae varies between 15 and 20 mm, depending on the chosen measuring points on the annular plane. The distance from the annular plane to the end of the tip is 45 mm.

The leaflets of the mitral valve are simulated by a 152 × 152 mm sheet of dark medium dental dam (Coltène Whaledent, Altstätten, Switzerland) (Fig. 4). Dental dam is also known as 'rubber dam' or 'Kofferdam'. It is a thin sheet of latex, commonly used in endodontic surgery and is especially designed to retain

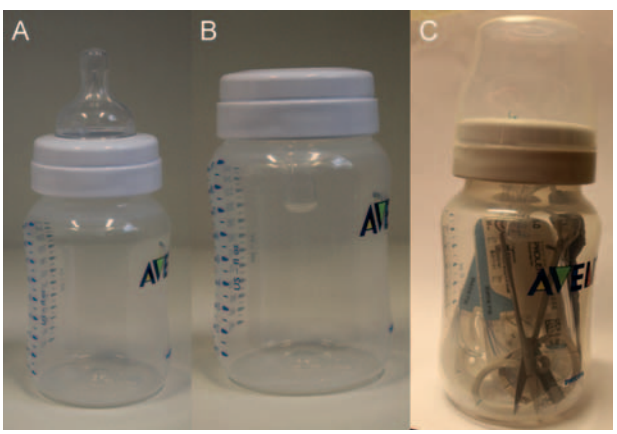


Figure 1: (**A**) Classic baby bottle, the associated feeding teat and screw ring. (**B**) Simulation position of feeding teat. (**C**) Storage container.

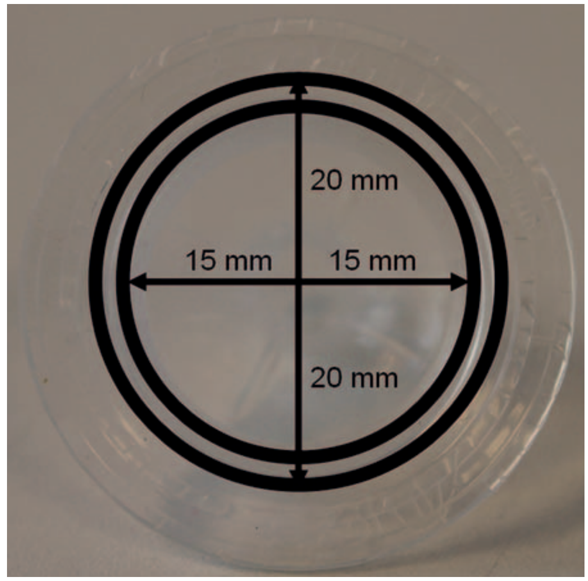


Figure 2: Dimensions of the simulated annulus.

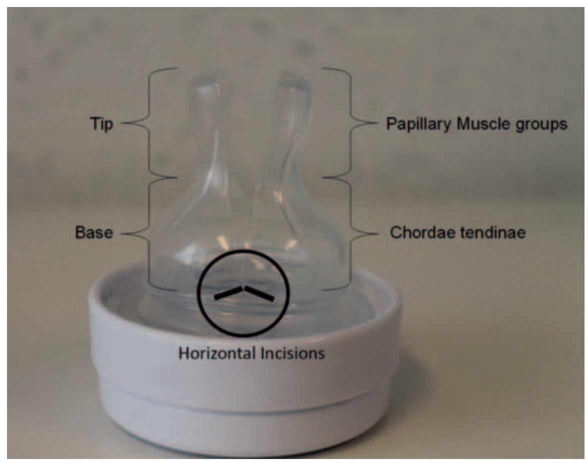


Figure 3: The subvalvular apparatus with simulated chordae tendinae and papillary muscle groups.

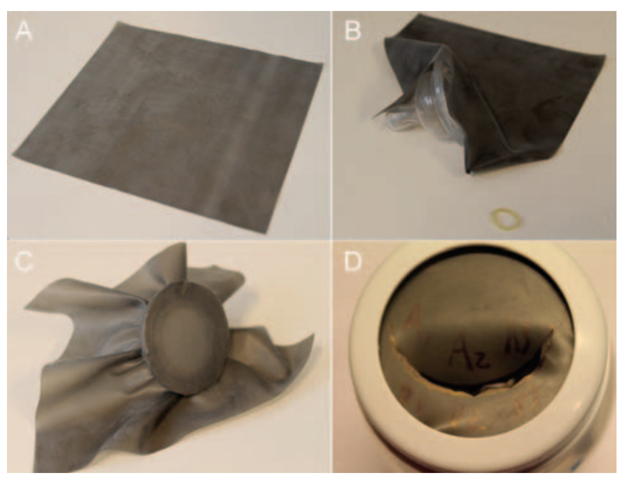


Figure 4: (**A**) Square sheet of dental dam. (**B**) Main simulation components; Feeding teat, dental dam, Tru-Force® elastic. (**C**) Assembled components. (**D**) Simulated leaflets and orifice.

its special properties when perforated or cut, which prevents rupture of the sheet when force is applied. The dental dam was extensively tested for maximum suture tension with a digital force gauge and its reaction to repeated suturing with 5–0 polypropylene sutures (Ethicon Inc., Somerville, NJ, USA) was documented. The dental dam was stretched over the base of the teat and was fixed with one Tru-Force® orthodontic elastic of 9.5 mm diameter (TP Orthodontics, LaPorte, IN, USA). The excess portion of the dental dam was cut away (Fig. 4).

The screw ring was customized. The original outer diameter of the screw ring is 60 mm; the inner diameter is 33 mm and covers the entire base of the feeding teat. To make the base of the teat suitable for simulation, the inner diameter of the ring was milled out to 42 mm on a lathe. Finally the teat, covered with dental dam, was placed upside-down in the baby bottle and held in place with the modified screw ring (Fig. 4).

To complete the simulator, the mitral valve orifice was created by cutting the familiar semi-lunar shape in the stretched dental dam. The anterior, middle and posterior scallops of the anterior and posterior leaflet are drawn with a surgical marker on the dental dam (Fig. 4). If necessary for the simulation, there is unlimited scope to cut other structures, such as indentations, clefts or even tricuspid valve leaflets, out of the dental dam.

Various pathological conditions, according to Carpentier's Functional Classification [9], were simulated by changing the dental dam completely or simply by changing the stretched shape of the dental dam. For example, to mimic a P2 prolapse, the Tru-Force® elastic was loosened at the level of P2 and the dental dam was pulled in the direction of the A2 scallop.

The limitation of space by the left atrium was simulated with an ordinary 60 × 80 mm PVC adapter on the screw ring. Different surgical approaches, in both open and minimally invasive surgical methods, were simulated by adjusting the length of the PVC adapter or integration of the model in the I-Sim Laparoscopy Simulator (iSurgicals, Lancashire, UK) (Fig. 5).

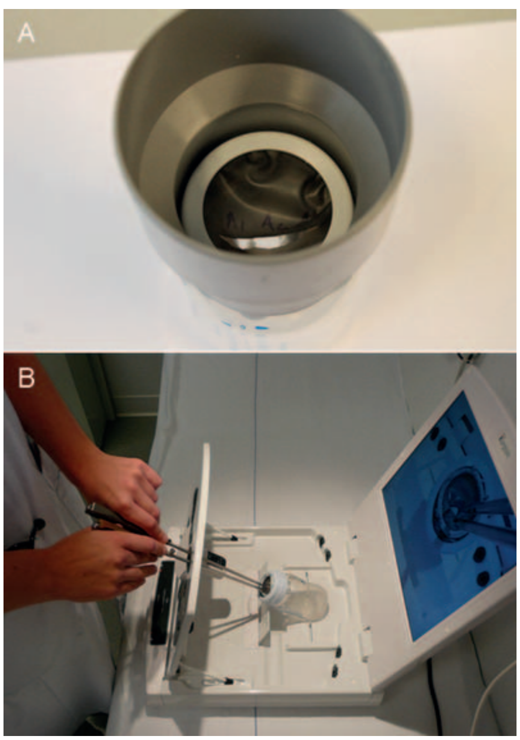


Figure 5: (**A**) Simulated left atrium. (**B**) Set up for minimally invasive training.

Supplementary Video 1: Assembly and tailoring of the simulator.

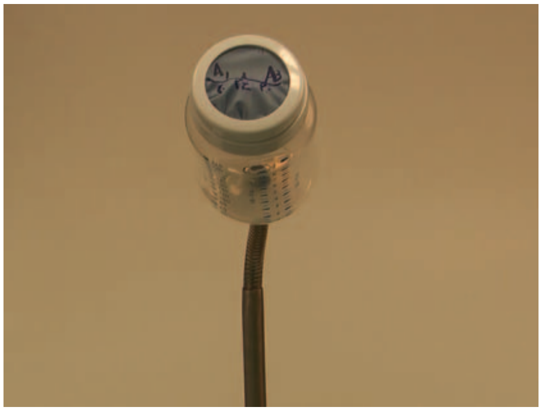
The above-described assembly and tailoring of the simulator is shown in Supplementary Video 1.

RESULTS

This study resulted in a simulation model very similar in size to the actual anatomical dimensions of the mitral valve. The average mitral annular cross-sectional area ranges from 5.0–11.4 cm^2 in normal human hearts, with an average of 7.6 cm^2 [10]. This model has a cross-sectional area of 7.0 cm^2. The length of the simulated chordae and papillary muscle groups is similar to the real anatomical arrangement [11]. Slightly different is the shape of the mitral annulus. The normal human mitral annulus is roughly elliptical and in three-dimensional space the annulus is saddle-shaped. This model has a flat, circular annulus, which gave an advantage in training because the flat plane of the annulus requires extra attention to needle positioning in the needle holder for optimal placement of the sutures. The use of 0% bisphenol-A silicone resulted in a tactile response to suture placement. The tensile strength of one 2–0 Ti-Cron suture in the silicone annulus, with a 10 mm wide and 1.5 mm deep bite, was 42.11 N/m^2, equal to 4.29 kilogram-force meter. A 5–0 polypropylene suture, inserted 2 mm from the edge of the dental dam, withstood a tensile load of 11.15 N/m^2 before tearing of the dam, equivalent to a weight of 1.14 kg.

It was possible to simulate the complete range of Type I and Type II valve dysfunctions: simulation of Type III valve dysfunction was limited to Type IIIa. This provides sufficient scope for training in the various surgical procedures described below (Supplementary Video 2).

Simulating Type I dysfunction, remodelling annuloplasty could be performed (Fig. 6). In the simulation of Type II dysfunction with anterior leaflet prolapse, it was possible to perform leaflet triangular resection, implant artificial chordae or chordae loops (Fig. 7) and modified papillary muscle sliding plasty. Simulation of Type II dysfunction with posterior leaflet prolapse resulted in the possibility of training in triangular leaflet resection, quadrangular leaflet resection with annular plication combined with leaflet height adjustment (Fig. 6), sliding leaflet technique, Z-shaped sliding plasty and indentation closure. Simulation of Type II dysfunction, with commissural or bileaflet prolapse, made it possible to practice the 'magic stitch' [12] and large annular plication technique. Simulation of surgical procedures with Type IIIa, restricted leaflet motion, were limited to the



Supplementary Video 2: Use of the simulator.

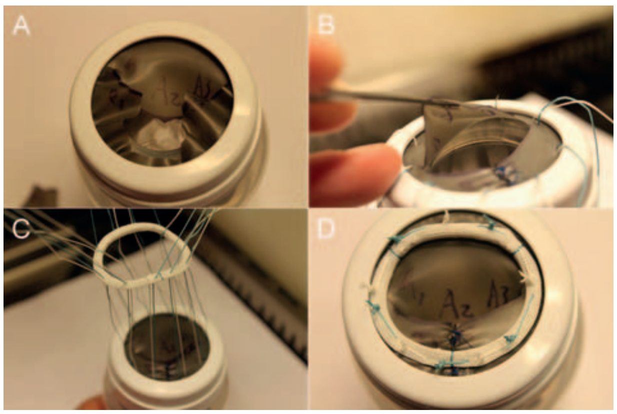


Figure 6: (**A**) Quadrangular resection of P2. (**B**) Assessment of depth bite. (**C**) Positioning of rigid ring. (**D**) Completed quadrangular resection with height adjustment and remodelling annuloplasty.

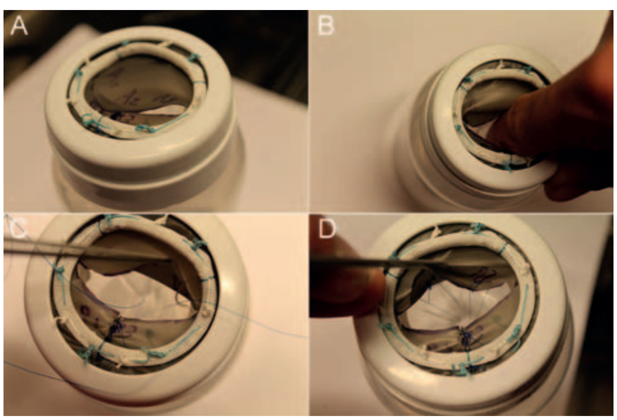


Figure 7: (**A**) Remaining A1 and A3 prolapse. (**B**) Knot tying through annular orifice. (**C**) Placement of improvised neochordae on papillary muscle groups. (**D**) Assessment of suture placement inside the valve.

performance of commissurotomy and pericardial patch extension of both the anterior and the posterior leaflet.

In addition to all the techniques described above, it was possible to practice several other techniques in this study model, including both mechanical and biological valve replacement with posterior leaflet preservation (Fig. 8), edge-to-edge technique, annular decalcification with annular reconstruction using pericardial tissue, and correction of systolic anterior movement was possible by performing posterior or anterior leaflet height reduction.

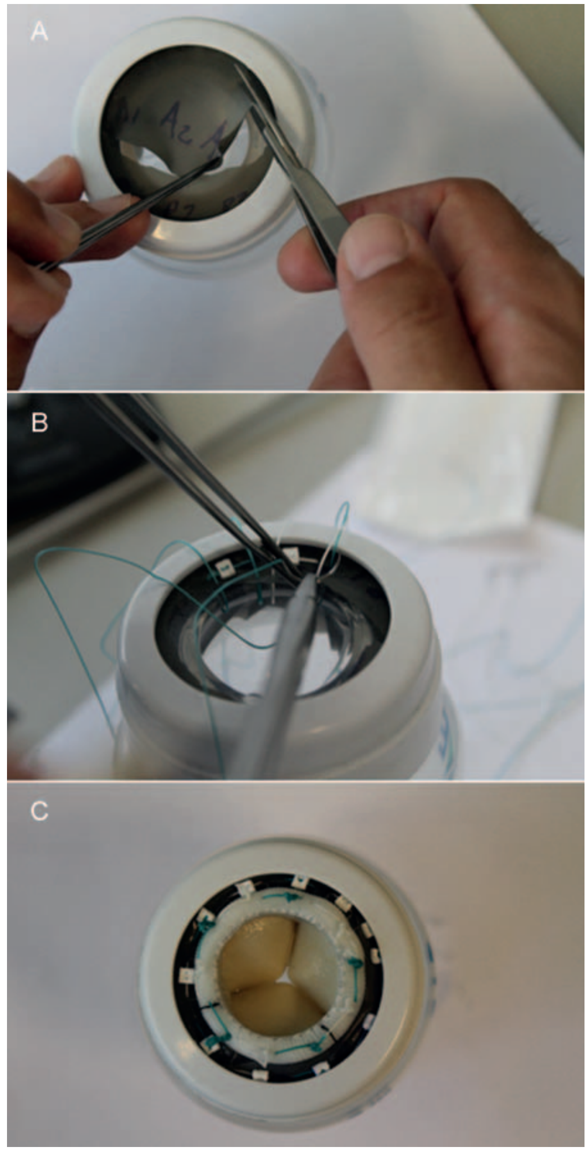


Figure 8: (**A**) Resection of the complete anterior leaflet. (**B**) Suture placement for valve implantation with folding the posterior leaflet. (**C**) Implanted Carpentier-Edwards Perimount pericardial bioprosthesis.

By adapting the dental dam to the anatomical configuration of the tricuspid valve, it became possible to perform a wide range of tricuspid valve reconstruction surgery, including annular remodelling, modified Kay plasty and DeVega plasty.

The use of commonly available materials resulted in a low-cost study model. Total costs of the study model were €5.14. With the additional PVC adaptor—and depending on the length required—the cost did not exceed €9.

DISCUSSION

This study resulted in a low-fidelity, low-cost, reusable and portable simulation tool, on which almost the full range of mitral valve surgery techniques, in both the classic open- and minimally invasive approaches, could be practiced. During its creation process we discovered that nearly the full range of tricuspid valve reconstruction surgery could also be simulated on the model. To the best of our knowledge, this is the first low-fidelity model ever described, in which all of the above-mentioned techniques can be rehearsed. At present, one low-fidelity mitral valve simulator is commercially available, manufactured by the Chamberlain Group. The Chamberlain simulator has been well-received in academic and medical device circles since its introduction in 2002 although, in our opinion, it has several disadvantages [5]. It is only possible to practice one or two procedures out of the wide range of mitral valve surgery techniques; the device lacks the very important subvalvular apparatus and the model is only moderately pliable, which permits only a limited degree of traction and relaxation during suture placement [3]. Additionally, the simulator is designed for one-time use only if leaflet resection is performed. Costs could be as high as US$105 for a single training session in, for example, quadrangular leaflet resection.

As a low-fidelity simulation, our simulation model is perfect for novice learners: an important feature is that it can be disassembled into teachable components, and its handling and the developed skills of a trainee can be assessed objectively by a supervisor. In mitral valve surgery, one of the most important skills is correct suture placement in both the annulus and the leaflets. The greatest advantage of this study model is the transparency of the simulated mitral annulus and subvalvular apparatus. This permits objective assessment of the depth of bites and spacing between sutures. As well as transparency, our model provides inferior access to the valve through the trainer base, which is also possible in the New Mitral Valve Prolapse Trainer of the Chamberlain Group.

Other benefits of our novel low-fidelity simulator, for both mitral valve and tricuspid valve surgery, are that the silicone ring tolerates real-life traction and is reusable for up to approximately 45 suture placements. This model is easy to assemble and components are available worldwide; it is easily portable and materials can be stored inside it.

This simple and versatile tool has the potential to provide an even more comprehensive training platform for aspiring cardiothoracic surgeons and can be made and used virtually anywhere. With its ability to simulate a wide range of scenarios in mitral valve surgery, this model may contribute to the development of technical skills and procedural knowledge required for adequate performance in the operating room. Further studies are needed to validate and evaluate this novel simulation model in order for it to be an effective training platform in the cardiothoracic surgery residency program.

SUPPLEMENTARY MATERIAL

Supplementary material is available at *ICVTS* online.

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Conflict of interest: none declared.

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