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A high fidelity tissue-based cardiac surgical simulator

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Abstract

Objective: Issues concerning the training and certification of surgical specialists have taken on great significance in the last decade. A realistic computer-assisted, tissue-based simulator developed for use in the training of cardiac surgical residents in the conduct of a variety of cardiac surgical procedures in a low-volume cardiothoracic surgery unit of a typical developing country is described. The simulator can also be used to demonstrate the function of technology specific to cardiac surgical procedures in a way that previously has only been possible via the conduct of a procedure on a live animal or human being. **Methods**: A porcine heart in a novel simulated operating theatre environment with real-time simulated haemodynamic monitoring and coronary blood flow, in arrested and beating-heart modes, is used as a training tool for surgical residents. **Results**: Standard and beating-heart coronary arterial bypass, aortic valve replacement, aortic homograft replacement and pulmonary autograft procedures can be simulated with high degrees of realism and with the superimposition of adverse clinical scenarios requiring valid decision making and clinical judgments to be made by the trainees. **Conclusions**: The cardiac surgical simulation preparation described here would appear to be able to contribute positively to the training of residents in low-volume centres, as well as having the potential for application in other settings as a training tool or clinical skills assessment or accreditation device. Collaboration with larger centres is recommended in order to accurately assess the utility of this preparation as an adjunctive cardiothoracic surgical training aid.
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Keywords: Surgical simulation; Resident training; Cardiac surgery

1. Introduction

In Jamaica, a typical developing country, a chronic shortage of intensive care services has resulted in the under-delivery of cardiac operations to the population, and therefore to an under-exposure of trainee surgeons to cardiac surgical techniques (approximately 80 procedures per year). These conditions also adversely affect the training opportunities of cardiac surgical operating theatre nursing staff.

In the long term, only the provision of more intensive care facilities will impact on the problem of an ever-growing waiting list for cardiac surgery in developing countries. In the interim, it may be possible to utilize simulation technology to supplement the existing methods of teaching certain aspects of cardiac surgical procedures to surgical residents and operating theatre nursing students. In recent times, the role of simulation in the training of medical personnel has become an important issue [1–6]. Efforts to introduce simulation-based training scenarios in surgery have concentrated on video-assisted minimally invasive procedures for the most part, as a response to the difficulty of creating hi-fidelity tissue interactions with the trainee [1–5]. To date, there have been few publications describing a truly realistic simulator for a cardiac surgical procedure [7,8].

It was the aim of our research team to develop a cardiac surgical simulator using an explanted porcine heart as the model for the human heart. Our goal was to render the mechanical component of the simulator in such a fashion as to be finely controllable by a computer interface. We endeavored to encode within that computer interface algorithms of sufficient complexity so as to be able to conduct several different types of simulated cardiac surgical operations in a realistic and educationally rich manner, thereby allowing the trainee surgeon to acquire certain cardiac surgical technical skills previously attainable only by exposure to human subjects or live animal models.

The simulator described here provides the trainee surgeon and supervisor with a tissue-based cardiac surgical simulation substrate in an environment that realistically mimics an actual procedure. Initial reaction to the existing

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device from surgical residents as well as trained cardiac surgeons has been extremely favorable. Additional details of the electromechanical engineering design and computer programming aspects of the simulator have been previously published [9,10].

2. Materials and methods

All materials and engineering utilized in the cardiac surgical simulator were designed and constructed, or modified for use, by our research group. Porcine hearts are used for simulated cardiac surgical procedures. The hearts are obtained from abattoirs from animals killed for consumption and are prepared for use by one of the authors (PSR). No animals are sacrificed specifically for use in the surgical simulation exercise. Preparation entails dissection of the mediastinal lymph nodes, portions of the liver, and the trachea and proximal pulmonary hilar structures from the heart to expose the great vessels. The pulmonary venous orifices are uni-focalized and a latex balloon (12″ commercially available helium grade latex) is inserted into the left ventricular cavity and secured by a left atrial purse string suture. Another balloon (fashioned from a large 12″×1″ latex Penrose drain) is placed into the right ventricle via the superior vena cava and advanced into the right ventricular outflow tract and main pulmonary artery as far as the bifurcation, and secured with a ligature. After such preparation, the hearts are stored in 40% alcohol solution at 4° C until use. The simulated pericardial well is a silicone basin constructed, textured and pigmented to appear similar to a standard open pericardial cavity. The well is positioned within the thoracic cavity of a mannequin in an anatomically correct orientation to simulate a standard median sternotomy. Stay sutures are not utilized in the preparation as it presently exists. The edges of the thoracic cavity and pericardial well are made of silicone-coated rigid plastic foam, painted prior to coating to resemble the skin, subcutaneous fat, and divided sternal bone; this layer of the simulated chest wall is rigid enough to support the placement of standard sternal retractors in the manner utilized in an actual procedure. The proximal ends of the intra-ventricular balloons are mated to 1/4″ tubing connectors and are attached to the tubes at the cephalad end of the simulated pericardial well, and the porcine inferior vena cava is similarly secured to the postero-caudal wall of the pericardial well by another 1/4″ tubing connector. The aorta, which is trimmed to approximately 10 cm in length, is brought through a silicone tunnel in the cephalad end of the simulated pericardial well and the open end is then cross-clamped and the clamp is hidden under a drape. This results in a four-point fixation of the porcine heart within the pericardial well. The tubes mated to the intra-ventricular balloons exit the pericardial well and are connected to the computer controllable pumping mechanism. The pump is a programmable linear actuator (UltraMotion®, Ltd, Mattituck, New York) that is configured to compress a pneumatic bladder. The system is closed, such that the amount of air within the bladder, tubes, and intra-ventricular balloons is constant at any given time. It is also possible to increase or decrease the amount of air present within the system using a three-way stopcock valve and syringe arrangement. When connected, it is difficult for the subject to see the tubing, as they enter the heart from its posterior aspect. The four-point fixation of the porcine heart, with two of the points being at the inflow of the pneumatic lines, results in a realistic configuration of the heart within the pericardial cavity, and allows the heart to remain connected to the pumping mechanism and to continue beating realistically even when partially enucleated from the cavity. A perfusion line is introduced into the aortic arch and hidden by a drape. The perfusion line is connected to a roller pump which operates in series with another roller pump, which functions as an intra-operative pericardial sump suction pump such that an amount of simulated blood in the system (approximately 500 cc) is held constant, and is continuously circulated through the coronary arteries, coronary veins and coronary sinus, atrial and ventricular chambers, and out of the heart and into the pericardial well via small fenestrations made in the coronary sinus and posterior aspect of the right atrium, then back to a reservoir for re-circulation. The simulated blood is a water color pigment which is optically opaque and does not stain the tissues, in contrast to simple food coloring dyes. Another separate pneumatic pumping system imparts movement of the lateral walls of the simulated pericardial well in a manner evoking the movement of the lungs, which are mimicked by two additional balloons placed adjacent to the lateral outer walls of the pericardial well, during positive-pressure ventilation (Fig. 1). The movement of the 'lungs' in

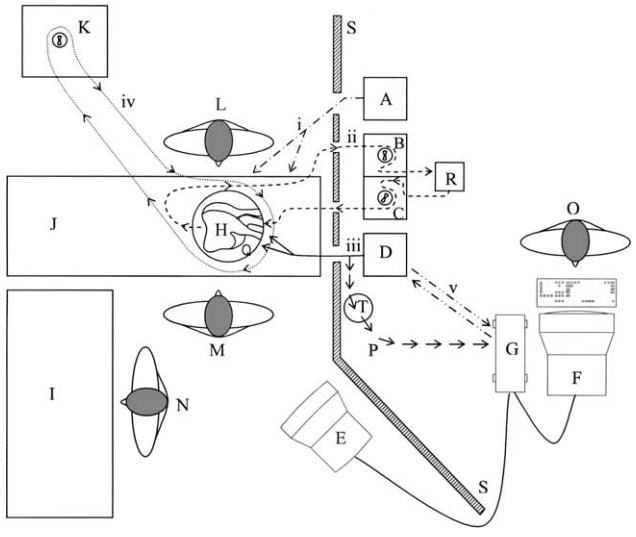

Fig. 1. Schematic Diagram of Simulation Scenario. Key (A) Pneumatic pulmonary pump. (B) Hydraulic suction pump. (C) Hydraulic coronary pump. (D) Pneumatic ventricular pump. (E) Simulated intra-operative vital signs monitor. (F) Control monitor. (G) Central Processing Unit. (H) Porcine Heart. (I) Instrument table. (J) Operation bed with simulated patient. (K) Hydraulic pump for mock bypass circuit. (L) Surgical Trainee. (M) Supervising Surgeon. (N) Scrub Nurse. (O) Simulation Operator. (P) Pressure Feedback loop. (Q) Pericardial cavity. (R) Fluid Reservoir. (S) Screen. (T) Transducer. (i) ⇢ tubing to right and left simulated lungs. (ii) ⇢ tubing circuit from pericardial suction to coronary perfusion. (iii) → tubing from ventricular pump to intraventricular baloons. (iv) ⟶ tubing for mock bypass circuit (pre-cannulation). (v) ⇠⇢ serial connection between ventricular pump and central processing unit.

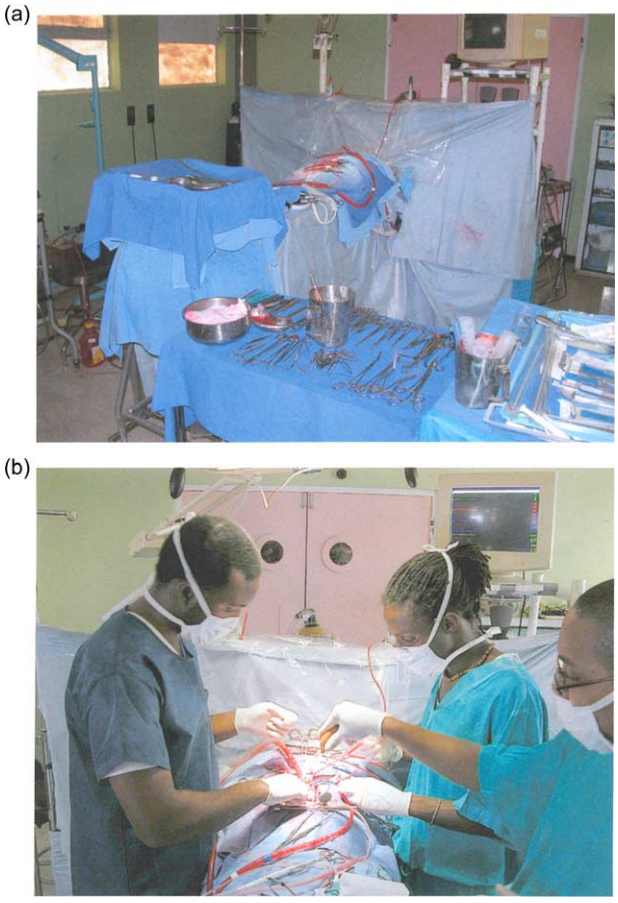

Fig. 2. (a) The simulation environment. (b) Simulation in progress.

the simulation can be finely adjusted by increasing or decreasing the amount of air in the pulmonary circuit (i.e. simulated 'tidal volume' is variable), thereby increasing or decreasing the movement of the lateral walls of the simulated pericardial well. The simulated operating environment is configured to resemble a typical cardiac surgical procedure set-up, including the use of surgical drapes (Fig. 2).

A Pentium® IV PC computer serves to control the intraventricular pumping mechanism of the simulation. The simulation control software and user interfacing was designed and implemented by our group, utilizing a Linux-based operating system and JAVA as the programming language. An intra-operative monitor that is controlled by the simulation software and synchronized to the mechanical activity of the pump reflects intra-operative physiological parameters in real-time. Simulated parameters include the electrocardiogram, systemic arterial, central venous, and pulmonary arterial pressure tracings, and core body temperature. The entire environment is as true to the actual situation as is possible, in order to achieve the phenomenon known as 'suspension of disbelief'. This is the vital component of a simulation which provides the experience with the sense of reality necessary to impart to the subject the perception that he/she is actually performing the task that the simulation is designed to emulate. It follows therefore that all equipment and instruments utilized in the simulated operation are identical to those used in an actual procedure.

2.1. Coronary arterial bypass (CABG) simulation

The simulation scenario is commenced by informing the subject that the 'patient' is on the operating table, with the chest opened and graft conduits harvested by resident staff. If remnants of human saphenous veins from actual procedures are unavailable, we have found that excised bovine coronary arteries are an excellent, almost identical substitute (Fig. 3). These are prepared by dissecting the left anterior, circumflex, and right coronary arteries from a bovine heart, and tying or clipping the side branches. The conduits are then stored in 40% aqueous alcohol at 4° C until use.

The subject is briefed on the details of the patient's preoperative history. Aspects of the simulated patient's history which can be anticipated to affect the course of the simulation are programmed into the software as variables for which specific events (such as cardiac rhythm and rate changes, blood pressure changes, core temperature changes) can be triggered either by the software in response to stimuli from the operative field, as a scheduled event where a change occurs after a specified time has elapsed in

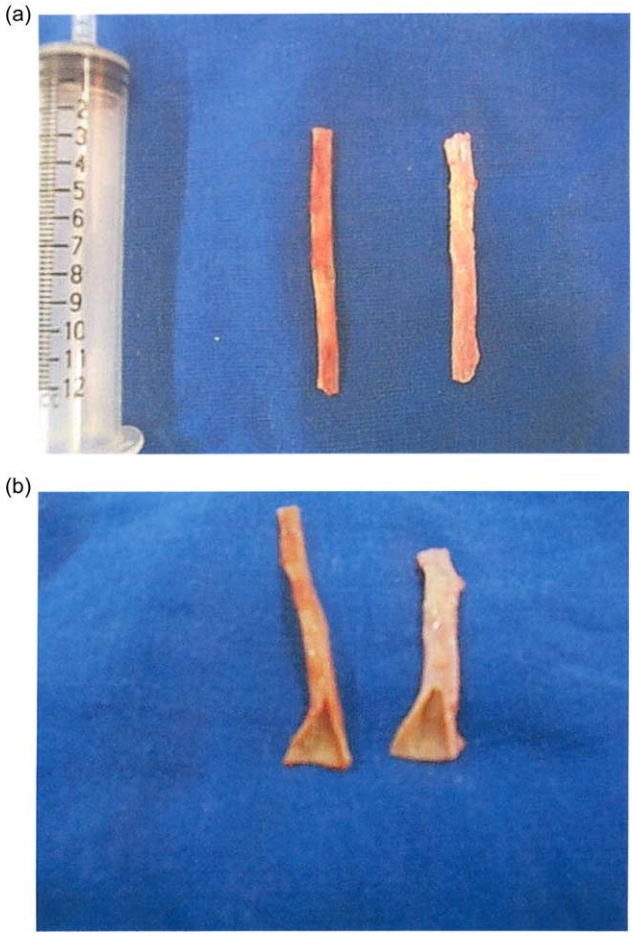

Fig. 3. (a) and (b) Comparison of human saphenous vein (left of each pair) with harvested bovine coronary artery (right of each pair) as conduits.

the operation or since the last time a specific keystroke was chosen, or as an immediate event occurring after direct keystroke inputs into the scenario by the simulation controller (who plays the role of the anaesthetist), or by the assistant surgeon, who is the subject's supervisor, via an accessory keyboard positioned out of the line-of-sight of the trainee. An essential feature of the simulator is the use of a feedback loop based on closed-system pneumatic pressure measurements, which allow the computer to 'know' that the heart is being handled, and to subsequently initiate different pumping patterns in response to such handling. This effect is accomplished by the placement of a pressure transducer on a side-arm of the closed system, where measurements of changes in pneumatic pressures are converted to micro-voltage signals and then used to create a scale of increasing signal intensities which function as a series of thresholds. When a threshold is exceeded, a pre-programmed algo-rhythmic pathway or multiple pathways can be followed leading to a specific mechanical behaviour of the pumping system. For example, if the patient's 'angiogram' had shown left main coronary artery disease, then the program could be designed to have a low threshold for the initiation of a variety of cardiac dysrhythmias whenever handling of the heart was detected by the sensor system, including ventricular fibrillation which would then require the heart to be 'defibrillated' using internal paddles at appropriate energy settings (Fig. 4). Several other dysrhythmias (atrial fibrillation, supraventricular tachycardia, nodal rhythms, ventricular tachycardia, bradycardia, heart block, ventricular ectopic beats) can be simulated and correlated to the electrocardiogram tracing on the intra-operative monitor and the mechanical activity of the heart. As with ventricular fibrillation, any of the cardiac rhythms can be initiated either by threshold triggering, or by direct keystroke input by the simulation controller. If the patient was said to have had poor left ventricular function on echocardiography, then a 'low pressure, high irritability' mode of operation of the simulator pump would be the primary setting used during the entire procedure. In this setting, a low threshold for triggering dysrhythmic activity and/or pre-cardioplegia hypotension can be chosen. This setting could also entail a low-cardiac output state at the end of the grafting phase of the procedure, which would require the subject to make decisions regarding the use of inotropes or balloon pumping at that stage of the operation. The subsequent

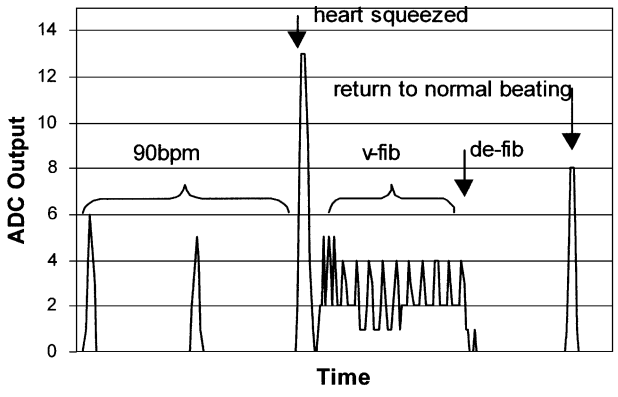

Fig. 4. Graphical representation of pressure sensor feedback loop function.

'administration' of drugs or the institution of balloon pumping can then be simulated, with the expected response shown on the monitor screen (e.g. the typical arterial pressure tracing and readings associated with balloon pumping) and in the behavior of the heart in the operating field. In the present set-up, the actual process of inserting the balloon is not simulated, as the emphasis is on the decision-making process (i.e. the need to institute balloon pumping) rather than the physical act of balloon insertion. The onus is also on the trainee to choose the appropriate drug or therapy, and in the correct dosage; if incorrect, the effects of such errors (overdosing or underdosing) can be mimicked in the simulation. All of these therapeutic maneuvers and the responses to them occur according to pre-programmed algorithms that can be activated by the simulation controller, the assistant (supervising) surgeon, or the 'anaesthetist', by means of keystroke input commands, or with apparent randomness initiated by the computer in response to the exceeding of the pre-set trigger thresholds. In the both situations, a degree of randomness is built into the software, by supplying multiple plausible logic pathways following threshold attainment or direct command input, such that it is not always possible for the subject or the supervising surgeon to precisely predict or anticipate any particular cardiac behavior in response to a given stimulus.

Simulation runs are classified as level I to level IV, in ascending order of difficulty for the trainee. During level I simulations, the simulated CABG procedure is then commenced as a standard, cardioplegic arrested operation. The trainee begins the simulation exercise by placing a standard aortic cannula into the aortic root of the beating heart preparation, and a single venous cannula into the right atrial appendage. This establishes a mock bypass circuit. Cardioplegia solution (water or simulated blood) is introduced into the aortic root after cross-clamping. At present, antegrade cardioplegia administration is used most often, for reasons of simplicity, although retrograde coronary sinus cannulation and cardioplegia administration is possible. Cardiac arrest does not occur as a result of the administration of the fluid, but rather as a response to a direct keystroke input by the simulation controller, timed to coincide with fluid administration. The coronary artery is opened in the usual fashion, requiring tissue handling, vessel exposure and target arteriotomy techniques identical to those employed in the human procedure, and the size of the target vessel is calibrated using graduated polypropylene probes. The largest passable probe size is noted, and the operation then proceeds following the same steps as an actual procedure. The time taken to construct each anastomosis is noted, as is the subjects' adherence to the standard CABG protocol, including the administration of boluses of cardioplegia at 20–30 min intervals in combination with topical ice slush to 4° C. The realism of the simulator is such that after approximately 30 min without cardioplegia and/or topical cooling, electrical activity on the vital signs monitor and mechanical activity of the heart in the operative field may commence spontaneously or by direct keystroke input command. Spontaneous commencement of cardiac rhythm is possible by designating the elapsed time since the last keystroke for cardioplegia as the trigger for mechanical activity, if the time exceeds 30 min, for example.

The computer would then utilize its internal clock to measure the elapsed time, and then proceed to initiate pumping, or not, depending on which logic pathway is followed. Similarly, if the core temperature reading, which is programmed to rise slowly after a keystroke indicates that the trainee has placed ice slush onto the heart, was to rise above a threshold temperature (e.g. 35° C), spontaneous rhythm, whether sinus, nodal, or fibrillation, could commence. In the simplest scenario, the heart 'tolerates' the entire procedure without incident, and sinus rhythm commences smartly after removal of the cross clamp, initiated by a keystroke command input by the simulation controller at the time of removal of the clamp, while the proximal anastomoses are being constructed in a standard manner utilizing a side-clamp. As the complexity of the simulation is increased, progressively more difficult clinical scenarios are encountered (level II simulations) and the subjects' response to each adversity can be recorded for discussion at the end of the simulation session. After construction of the proximal anastomoses and attainment of 'stable cardiovascular parameters', the simulation is terminated. During the entire procedure, a trainee operating theatre nurse is present and functions in exactly the same manner as would be required by an actual CABG procedure, under the supervision of an experienced nurse. The fidelity of the training experience may be even greater for the nurse than for the surgical resident, as there is no recognizable difference between an actual procedure and the simulated from the operative nursing perspective.

After the simulation is terminated, the distal anastomoses may be examined by transecting the conduit approximately 1 mm proximal to the suture line. The suture line is examined and can be graded with respect to spacing, angle of suture placement, number of throws, etc. Finally, polypropylene probes are placed through the anastomosis into the target vessel and the largest size that can be passed is again noted.

After it is judged that the subject can competently construct distal and proximal anastomoses under simulated cardioplegic arrest conditions, level III experiments are commenced. In level III, the simulated CABG procedure is conducted on the beating heart. Artificial blood is made to flow within the cardiac vasculature under pressure, and measures to control flow after opening the arteries are required, including snaring of the arteries or the use of intravascular occluders or flow-through shunts. Additionally, the 'lungs' continue to be active, imparting additional motion and difficulty in the operative field. We have found that the vigorous beating action in combination with high-pressure coronary flow and the imposition of haemodynamic changes as reflected on the vital signs monitor effectively mimics many of the technical challenges imposed by a true-beating heart procedure, and forces the trainee to adapt his/her anastomotic technique to the new conditions in a manner analogous to an actual beating heart procedure. In the simplest of these scenarios, the beating heart 'tolerates' the procedure uneventfully, including the use of epicardial stabilizers and varying degrees of cardiac rotation (Fig. 5). The properties of the simulation scenario allow all commercially available stabilizers to be utilized in the same manner as for an actual procedure, whether involving footplate compression or epicardial vacuum devices. As the complexity of the beating heart simulation increases, dysrhythmias and low-output states of increasing severity are encountered during the construction of the anastomoses and in the post-anastomotic phase (level IV simulation) and again the responses of the trainee to these adverse events are recorded and discussed after the procedure. The parameters utilized to evaluate the quality of the anastomoses are identical to those used in level I exercises. As such, the results of all phases of the experiment can theoretically be directly compared.

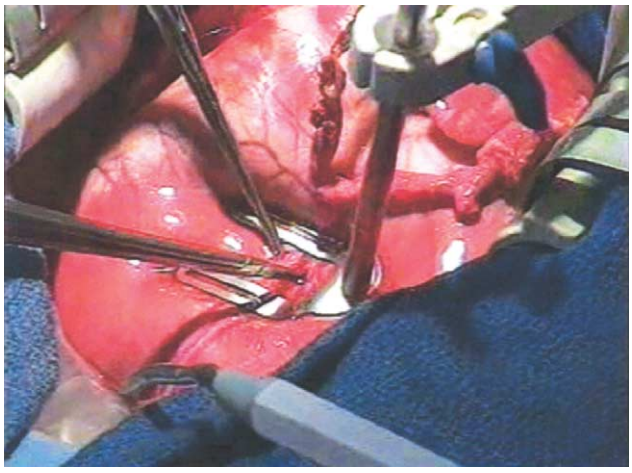

Fig. 5. Epicardial stabilizer in use in Level IV CABG simulation.

2.2. Aortic valve procedure simulations

Standard aortic valve replacement can be effectively simulated (Fig. 6). After cannulation for bypass, an aortic cross-clamp is applied, the aortic root opened, cardioplegia administered via the coronary orifices, topical ice slush placed into the pericardial sac and onto the heart, and cessation of mechanical and 'electrical' cardiac activity achieved. The aortic valve leaflets are excised, and interrupted annular sutures are placed in the usual fashion. Cardioplegia intervals of between 20 and 30 min are

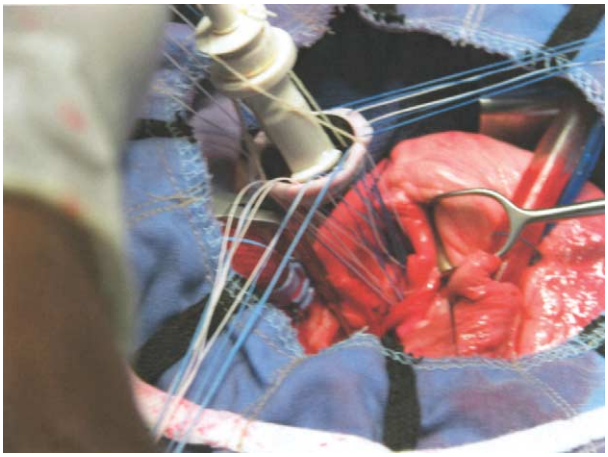

Fig. 6. Aortic valve replacement simulation. Valve about to be seated into aortic annulus.

observed, the time taken to perform the valve replacement noted, and the aorta closed. Once again, as in the CABG simulations, a variety of intra-operative scenarios may be encountered, ranging from dysrhythmias to low-cardiac output states, all requiring the trainee to make appropriate decisions and perform realistic maneuvers (defibrillation, placing of pacing wires, placement of haemostatic sutures, etc.) in order to complete the simulation exercise to the satisfaction of the supervising surgeon. At the end of the exercise, the aortic root is examined in detail, with special attention to the aortic suture line (which can be tested by pressurizing the aortic root with artificial blood solution), and the annular sutures, which are subjected to probe-patency testing to look for potential sites of paravalvular leakage.

2.3. Aortic homograft and Ross procedure simulations

The Ross Procedure (pulmonary autograft) or homograft aortic root replacement can also be very effectively simulated using this preparation. Bicaval venous cannulation is employed. As grafts, the aortic or pulmonary root from another porcine heart provides an excellent substrate. In addition, the trainee can be taught many of the technical aspects of autograft harvesting, on a still heart or on a beating heart with coronary flow, as the orientation of the pulmonary root in the simulation can be made to closely resemble actual human anatomy. For both conventional aortic valve replacement and homograft/Ross procedure simulations, it is envisioned that the use of a scoring system will allow for the tracking and assessment of the trainee's progress in learning these operations.

3. Discussion

The cardiac surgical simulator as described has allowed our surgical residents to be exposed to realistic procedures and would appear to have facilitated the acquisition of technical and cognitive skills in a manner which heretofore has only been possible by the conduct of an actual operation on a human subject or live animal model. While there is no doubt that real operations are the best way to acquire real surgical skills [11,12] there is an increasing acceptance of simulation exercises as a method of augmenting the processes leading to surgical competence [1–8]. The simulator provides hi-fidelity tissue interaction for the trainee surgeon. The results of other simulation studies suggest that sufficiently realistic simulation exercises can be used to track the progress of a trainee in acquiring technical competence, and may also be valid as tools to define, for the first time, the actual learning curve for specific technical skills [7,8]. There is no suggestion that the use of the simulator could supplant actual human operative experience, but rather that it can be used to introduce the foundations of technical and intra-operative management concepts in a controlled and reproducible manner, thereby giving a resident from a low-volume centre a realistic chance to compete when sent overseas to participate in a cardiac surgical team in a high-volume centre. In an era when it is proving progressively more difficult to secure funded training posts for candidates from developing countries in European or North American centres, it is conceivable that by employing simulation-based training the time needed to be spent abroad could be minimized, and therefore the funds necessary to support such a candidate while in the developed country, which are increasingly expected to come from the candidate's home country, could also be minimized. This may be no small consideration for a cash-strapped developing nation. In addition to helping to expose residents in developing countries to these experiences, where otherwise they might not be so exposed, it can be envisioned that this or similarly realistic simulation exercises could be used in the accreditation or re-accreditation of cardiothoracic surgical trainees or practitioners in any locale, with the reproducibility of any particular scenario allowing for an extremely standardized testing platform.

The argument can be made that less complex simulation exercises can be used to teach the technical aspects of coronary anastomoses, valve replacement, etc., without the need to replicate the operating theatre environment or adverse intra-operative cardiac function phenomena. Such bench preparations do exist and are useful to a point, and our group, and others, have developed and made use of such simpler preparations [7,8,13,14]. It is possible, however, that the addition of adverse conditions into the simulation scenarios, requiring the trainee to think and solve problems, in addition to simply placing sutures, may serve to strengthen the value of the training exercise, in a manner analogous to the use of complex flight simulators to train pilots and astronauts not only to perform under ideal conditions, but also to develop and rehearse responses to emergency situations [15].

There are several limitations to the simulator in its present form. Initial preparation of each porcine heart for use takes approximately 45 min; as a counter point, each heart can be used for between 15 and 20 coronary bypass grafts (5 or 6 complete triple bypass procedures) and several aortic valve replacements and Ross /homograft procedures. To this end, we have found that storage of prepared hearts in 40% aqueous alcohol for months before use is possible. The tissue remains soft, pliable and surprisingly lifelike when preserved in this manner. However, porcine coronary anatomy is similar, though not identical, to the human. A major difference is in the size of the circumflex branches, which we have found to be quite small, and therefore it is difficult, though not impossible, to simulate procedures involving the obtuse marginal branches. We are investigating modifications of the preparation to allow for simulated procedures on the mitral valve, which are not possible in the present configuration. It is also envisaged that the beating heart mode could be coupled to a closed chest model, similar to those in use elsewhere and used to simulate minimal access beating heart CABG or aortic surgery, or even robot-assisted CABG procedures [5,16]. Limitations of our local resources have not allowed us to explore these potential applications to date. The silicone pericardial cavity is presently not able to accept stay sutures, such as those used in facilitating exposure of posterior coronary branches, although future incarnations of the simulator could accommodate such a modification. We have not evaluated

post-anastomotic distal coronary flow rates as a quality control measure, as we do not have access to conduit Doppler flow measurement equipment. It is possible that such measurements could be incorporated into future studies, however until now we have been forced to rely on lumen sizing as a measurement of anastomotic patency. An additional limitation is the inability to simulate mammary artery harvesting and utilization, although we are investigating the possibility of using porcine mammary artery specimens as conduits in future simulation runs. Each simulation exercise is time consuming, taking as long as an actual operation, excluding the time needed to open the chest, harvest conduits, and close the chest. Thus, a considerable commitment to the process on the parts of the trainee and the supervisor is required. On the other hand, in a low-volume cardiac surgical center, such a commitment may represent time invaluably spent. While the hearts utilized in our laboratory have been donated free of charge, continued development of the model and use on a larger scale would require the purchase of these materials. The electromagnetic motor of the pump does make some noise, which in theory could negatively affect the realism of the exercise, although the pump can be placed in a different, remote location to minimize this problem. The software created for the preparation is still in an early stage of development, and it is envisioned that future generations of the software will allow for almost infinite modification of scenario details, as well as for real-time computerized annotation of the trainee's decisions and interventions, allowing for easier post-procedure analysis. We also recognize that because of the small number of surgical residents (i.e. two) that have been exposed to this apparatus, any conclusions regarding the usefulness of the preparation are subject to sample-size bias. We are currently amassing data using assessment systems similar to those described by others [5,7], however the limited availability of suitable subjects upon which to conduct such research, and the shortage of funds necessary to facilitate these studies, are a serious hindrance to our efforts to provide meaningful data and conclusions. Further development and refinement of the preparation is ongoing, and it is hoped that collaboration with surgeons and trainees in other centres will be possible in order to increase the power and validity of any conclusions regarding the usefulness of this preparation as a cardiac surgical training tool.

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This work is currently under US Patent and Trademark Office review (USPTO Patent Pending # 10/405,809).

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejcts.2004.12.049

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