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Current Trends and Future Developments in Robotic Cardiac Surgery

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ABBREVIATIONS

AF= atrial fibrillation
ASD= atrial septal defect
IMA= internal mammary artery
LAD= left anterior descending coronary artery
LCX= left circumflex (coronary artery)
LIMA= left internal mammary artery
MI= myocardial infarction
TECAB= total endoscopic coronary artery bypass

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BACKGROUND

Robotic Cardiac Surgery has revolutionised operating for surgeons to provide less operative pain, shorter hospital stays and improved quality of life. As surgeons are constantly trying new techniques, Robotic Cardiac Surgery now encompasses mitral valve surgery, coronary revascularisation, atrial fibrillation surgery, pacing lead implantation, congenital cardiac operations, cardiac tumours resection and diaphragmatic pacing. Robotic technology is gradually becoming more affordable and so more centres are investing in training surgeons in these techniques. As a result, robotic cardiac surgery has developed into a rapidly evolving speciality with exciting new possibilities.

MITRAL VALVE SURGERY

The first robotic mitral valve repair was by Carpentier in 1998 with an early prototype robotic device.[1] Since then, the da Vinci® robot, approved for mitral valve surgery in 2002 have demonstrated excellent operative results and functional outcomes with a completely thoracoscopic approach.[2] A 3-5 cm incision is usually necessary to pass sutures and needles into and out of the chest. However recent advances in 3 dimensional (3D) visualisation and instrumentation, particularly the development of the robotic left atrial EndoWrist® retractor have increased the ease with which totally endoscopic mitral valve procedures can be carried out.[3] These microprocessor controlled mechanical wrists allow for motion scaling, reduced gross hand movements and the performance of micro-scale tasks that would otherwise be impossible.[4]

Since the mitral valve lies in the sagittal plane of the body, the right chest approach used in robotic surgery gives and excellent en face view of the entire valve. Techniques such as chordal reconstruction require a clear view, deep into the ventricle which the robot can offer. The correct placement of sutures within the fibrous head of the papillary muscles is greatly aided by the robotic enhanced 3D-visualisation. This is also useful in re-approximation, and for exact realignment and prevention of an uneven coaptation edge.

A study by Cheng et al (2009)[5] sought to review the surgical outcomes of their initial 120 robotic mitral valve repairs, with the first 74 repairs done using the first-generation da Vinci robot, and the final 46 performed with the newer da Vinci Si HD model. All patients received an annuloplasty band and 1 or more of the following: leaflet resection; annuloplasty; basal chord transposition, polytetrafluoroethylene neochordal replacement, or both; and edge-to-edge repair. There was 1 hospital mortality and 5 patients required mitral valve replacement for a failed repair. None to mild mitral regurgitation was seen in 89% patients, moderate mitral regurgitation was seen in 8.4% patients, and severe mitral regurgitation was seen in 2.8%. They felt that the newer da Vinci Si HD system, with the addition of an adjustable left atrial roof retractor, improves mitral valve exposure, enhancing the surgeon's ability to repair and test the valve and provided a comprehensive and reproducible approach.

These new additions to the robot as offer a greater range of motion for complex cutting angles and needle loading within the confined space, particularly of the left atrium in patients with mitral valve disease. Moreover, placing the challenging annuloplasty sutures at and around the lateral commissure is made easy because the axes of rotation of the needle driver are brought into the atrium.[6]

In terms of patient benefits and cost effectiveness, Woo et al. (2006) demonstrated that robotic mitral valve repairs had a significantly reduced blood transfusion rate and hospital stay compared to patients undergoing open repair via sternotomy.[7] The largest study done by Rodriguez et al included 300 patients over six years for which no conversions to sternotomy or mitral valve replacements were required. 7 patients underwent reoperation for bleeding and post discharge follow up revealed 66% had no/trivial mitral regurgitation, 23% had mild, 15% moderate and 2.2% severe MR.[8]

Despite the proven benefits of the robotic approach, currently the main drawback is resoundingly reported to be the lack of tactile feedback. Future models will provide improved 'haptic' feedback which takes advantage of a user's sense of touch by applying forces, vibrations, and/or motions upon the user. Incorporating haptic feedback into the master control interface can provide surgeons with the required perceptual information for navigation and optimal force application.

Ancillary devices used in valve repair will continue to complement the robotic setup. The use of nitinol U-clips has already shortened operative times significantly since the deployment of U-clips can be done more rapidly than the placement and tying of sutures endoscopically with less technical burden. [9] Current work is also underway on a complete ring with the necessary flexibility to allow support of the entire annulus in the robotic setting.[10]

Overall given recent evidence comparing outcomes with open mitral valve repair as well as the advantages in terms of visualisation, access and new techniques, robotic mitral valve repair is clearly rapidly developing and likely to become increasingly utilised by cardiac surgeons.

CORONARY REVASCULARISATION

Robotic Coronary revascularisation used initially only for internal mammary artery (IMA) harvest with a hand sewn anastomosis to the left anterior descending artery (LAD) has grown to encompass multiple approaches. These include off or on pump revascularisation with total endoscopic coronary artery bypass (TECAB). The TECAB is designed to carry out a single left internal mammary artery to the left anterior descending coronary artery bypass graft in a completely closed chest setting.[11]

TECAB ON BEATING HEART

Through two working ports and a camera port in the left chest both left and right internal mammary arteries may be harvested with electrocautery or a harmonic scalpel. Access is usually via a 3-4 cm anterior thoracotomy overlying the LAD coronary artery. A direct hand sewn anastomosis is carried out using a coronary shunt to maintain blood flow to the distal coronary while diverting it away from the operative field.[12] Motion stabilizers may be used to facilitate anastomosis on the beating heart. One of the latest techniques for this is via 'tissue deformation tracking' which provides virtual immobilization of the heart and forgoes the need of mechanical stabilizers. Tracking is done through use of landmarks to provide a stable frame of reference for making image registration. Landmarks can be either *natural* (prominent local features on the tissue surface) or *artificial* which are called fiducials (external markers with distinctive shape or color placed in vivo). The use of natural landmarks, such as vessel junctions and surface textures, has attracted significant interest in recent years. The main difficulty involved is in the consistency since they deform with the surrounding structure, a situation that is not encountered when using rigid, high-contrast external fiducials.

In this way, the tracking of soft tissue based on artificial landmarks is attractive in that it gives full control of the placement of the fiducials. However, these can sometimes interfere with the surgery itself, resulting in markers having to be placed away from the operating site, somewhat diminishing their value.[13]

TECAB ON NON-BEATING HEART

Advances in this procedure have seen it performed with cardiopulmonary bypass and the use of an endovascular balloon to occlude the ascending aorta so that cardioplegia can be instilled through a proximal part, arresting the heart and facilitating robotic anastomosis. Cardiopulmonary bypass is established through peripheral cannulation then the distal coronary anastomosis can be performed.[14] Gao et al competed a study in 2009[15] where 56 patients with severe stenosis in the left anterior descending artery (LAD), of which 10 cases had right coronary artery or left circumflex coronary (LCX) stenosis underwent robotically assisted endoscopic atraumatic coronary artery bypass surgery with the IMA manually anastomosed to the LAD or LCX on beating heart or Totally endoscopic coronary bypass graft, again on the beating heart. For all patients the IMA flow was checked by the Doppler flowmeter after anastomosis and CT scan and angiography revealed patent grafts in all patients at follow up.

A large single centre series with 150 patients undergoing

TECABs using both the beating and non beating heart techniques and bilateral internal mammary arteries was carried out by Surivastava et al. The rate of peri-operative MI was 2% and in 55 patients undergoing follow up computerised tomography angiography at three months, all 136 grafts were patent.[16] The largest multi-centre experience was reported by de Canniere et al. in 2007 involving five European institutions and 228 patients undergoing TECAB (117 on pump and 111 off pump) The overall mortality was 2% and conversion rate was 28% decreasing with time, and patency of grafts at six months was 97%.[17]

Currently, robotically assisted coronary revascularisation is mainly applied to a patient population requiring limited revascularisation usually to the anterior wall,[18] although the versatility of its use for other locations is gaining increasing favour. Novel systems for image guidance in totally endoscopic coronary artery bypass (TECAB) are also being developed. Figl et al.[19] aimed to augment the images in the endoscope of the da Vinci robot, by finding the transformation from the coordinate system of the preoperative imaging modality to the system of the endoscopic cameras. In a first step they built a 4D motion model of the beating heart with the heart surface taken from the motion model and registered it to the stereo endoscopic images of the da Vinci robot validation system using photo-consistency. The similarity function was found to be much smoother when using more phases and images of the vessels, from the preoperative coordinate system were then transformed to the camera system and projected into the calibrated endoscope view using two video mixers with chroma keying.

For training surgeons in this new modality, a study by Schachner et al. (2009)[20] assessed the learning curves and independent TECAB performance of 2 junior surgeons undergoing TECAB training. They performed portions of 44 robotic TECAB operations, including left IMA and right IMA harvesting, and IMA to left anterior descending coronary artery (LAD) anastomotic suturing. The procedure portions performed faster by the senior surgeon versus trainees were, in minutes (range), right IMA takedown, 35 (25 to 48) versus 49 (40 to 55); and LIMA to LAD anastomosis, 26 (12 to 100) versus 34 (24 to 67). After assuming senior roles in the robotic cardiac surgery program, the 2 trained surgeons performed 14 TECABs (LIMA to LAD) without the senior surgeon. LIMA takedown, 43 (27 to 70) minutes; LIMA to LAD anastomosis, 24 (15 to 60) minutes. This illustrates that TECAB can be well taught with a stepwise training program with independent performance after training to achieve an operation within adequate time limits.

ATRIAL FIBRILLATION (AF) SURGERY

The robotic da Vinci® system has been recently increasingly used in AF ablation through performing pulmonary vein isolation.[21] Robotics can provide effective visualisation and guidance for an ablating catheter around the posterior left atrium to form a box lesion around all four pulmonary veins.[22] A number of robotic mitral valve and atrial fibrillation (MV/AF) robotic procedures have been carried out using the Flex wave-10 microwave catheter.[23] Alternatively the robotic endoscopic Cox-Cryomaze technique has been developed using a warm beating heart strategy where a full set of left atrial argon-based cryolesions and closure of the atrial appendage are carried out.[24]

INTRACARDIAC TUMOUR RESECTION

Robotic surgery is increasingly applied for cardiac tumour resection, particularly in the context of the left atrial myxoma excision as this is the most prevalent cardiac tumour. Gao et al carried out a study in 2009 [25] where 19 patients with left or right atrial myxomas all underwent successful resections from the beating heart. The da Vinci® instrument arms were inserted through three 1-cm trocar incisions in the right side of the chest. Via 4 port incisions and a 1.5-cm working port, all the procedures were completed with a 30 degrees angled endoscope facing upward. Resection was successful in all patients and there was no tumour or septal leakage found in the complete 1- to 18-month follow-up. Aortic valve fibroelastomas have also be resected in this way.[26] The excision of Intracardiac tumours with the da Vinci robot® is therefore, efficacious, safe, and surgical results are excellent.

PACING LEAD IMPLANTATION

To achieve cardiac resynchronisation when percutaneous attempts to place the left ventricular lead have failed, this procedure needs to be done surgically. The total endoscopic robotic approach has been shown to have equal efficacy to the left lateral mini-thoracotomy approach and video-assisted thoracoscopic techniques.[27,28]

CONGENITAL CARDIAC CONDITIONS

Closure of atrial septal defects (ASDs) via robotic surgery is becoming increasingly common. Gao et al. carried out a large study of Secundum-type ASD (n=45) repairs with three cases of concomitant tricuspid valve repairs, using the da Vinci® with four port incisions in the right chest and a 2-2.5-cm working port. Cardiopulmonary bypass was achieved peripherally, aortic occlusion was performed with a cross-clamp, and antegrade cardioplegia was administered via the anterior chest. There were no incisional conversions and all the patients were successfully discharged.[29] Recently, the computer-enhanced robotic system has been applied to video-assisted thoracoscopic repair of patent ductus arteriosus (VATS-PDA). Suematsu et al. (2009) published a series where they utilized a voice-controlled robotic arm (automated endoscope system for optimal positioning: AESOP 3000 in VATS-PDA. Thirteen infants underwent robotically assisted VATS-PDA and this technique was found to give results comparable to closure via the conventional video-assisted thoracoscopic technique.[30]

Overall therefore, robotic surgery is feasible and safe for a number of paediatric surgical procedures, but evidence that it offers better clinical outcomes than conventional open or laparoscopic techniques is still lacking as we await randomised trials.[31]

DIAPHRAGMATIC PACING

Phrenic nerve pacing can eliminate the requirement for ventilatory support[32] and is most commonly performed for patients with quadriplegia and central alveolar hypoventilation. Other indications include intractable hiccups (singultus) and phrenic nerve injury.[33] When done via open surgery, a cervical approach requiring multiple neck incisions, a thoracic approach requiring multiple bilateral 5- to 7-cm anterior thoracotomy incisions or a sternotomy is required. [34]An endoscopic approach minimizes the number and size of incisions to three 1-cm incisions. The first 1-cm incision is made in the 4th intercostal space, 2 cm anterior to the anterior axillary line. The da Vinci robotic endoscopic camera, which is attached to a fiberoptic cable, is inserted, and entry into the pleural space is confirmed. Two additional 1-cm incisions, through which the right and left arms of the robotic system are inserted sequentially under direct videoscopic guidance, are made in the 2nd and 6th intercostal spaces.

The surgeon dissects a small segment of the left phrenic nerve free from the pericardium. The pacing lead is positioned around the nerve and affixed to the pericardium. The lead is passed through the robotic arm trocar site and attached to the receiver, which is implanted in a small subcutaneous pocket. Pacing is usually not begun around 4 weeks after the operation, to allow oedema and inflammation to subside. The goal is to maximize respiration with the least amplitude required for diaphragmatic contraction.[35] Insertion of a phrenic pacemaker with robotic assistance minimizes pain by avoiding multiple neck incisions, bilateral thoracotomies, or a sternotomy. This accelerates postoperative recovery and improves quality of life.

FUTURE TECHNICAL STRATEGIES IN ROBOTIC CARDIAC SURGERY

As the technological advances in robotic engineering increase, there are a number of concomitant advances in cardiac robotic technical enhancements. These are likely to take place in the following fields which are outlined below: image-guided surgical navigation, augmented reality, haptic feedback and perceptual docking with active constraints.

IMAGE GUIDANCE AND AUGMENTED REALITY (AR)

Augmented reality is the overlaying of graphic virtual images onto the real-life scene. The surgeon operates in a semi-immersive, interactive, three dimensional environment lending it to a wide number of applications in cardiac surgery. This includes training, preoperative planning and intraoperative enhanced visualization with graphic scans augmented over the top of the exposed surgical view for reference or guidance. It is used most notably for off-pump, TECAB surgeries on the beating heart where intuitive navigation, positioning and orientation of surgical instruments are pivotal. With traditional AR, depth perception can sometimes be a problem since it uses surface transparency overlays. Virtual objects can appear to float above the scene even though rendered at the desired depth i.e. if one object occludes another, it is perceived to be above it and so new approaches to avoid this are currently being developed. Bichlmeier et al.[36] have used a virtual mirror that relies on motion parallax to provide accurate depth perception. The method is intuitive but requires explicit extraction of the 3D tissue geometry, and optical tracking of both the patient and the surgeon. An AR approach by Lerotic et al.[37] called *inverse realism* has been developed to provide see-through vision of the embedded virtual object while maintaining salient anatomical features of the viewed surface. This provides realistic depth perception in the scene and is perceived as "X-ray vision" This is due to the exposed surface around the virtual object becomes transparent to provide a view through the surface so that two images can be combined together. In this way inverse realism can increasingly provide accurate depth perception for augmented reality and looks extremely promising for the future.

PERCEPTUAL DOCKING WITH ACTIVE CONSTRAINTS

In current robotic surgery, dexterity is enhanced by microprocessor controlled mechanical wrists which allow motion scaling for reduced gross hand movements and improved performance of micro-scale tasks. In pursuing more adaptive and intelligent robotic designs, the need of a tightly integrated control between the operator and the robot is increasingly important. *Perceptual docking* can be used for learning and knowledge acquisition in robotic surgery such that operator specific motor and perceptual/cognitive behaviour is acquired through *in situ* sensing. Humans have unexcelled flexibility and hand-eye coordination, as well as finely developed sense of touch. Our vision system is particularly superior in image understanding, feature tracking, 3D perception, morphological registration, and amalgamating a diverse sources of visual cues. Integrating this into executing dexterous surgical tasks under a static frame of reference for moving objects is one of the ultimate goals of robotic surgery The future clinical impact of the technology will rely on the machine intelligence of the system and its ability in bridging the sensory information such as vision and tactile feedback between the tool tip and human hands.

To avoid inadvertent tissue damage, this concept is used in combination with the concept of *active constraints* (or virtual fixtures). This means that if the tool approaches a volume of space previously defined to be forbidden, the robot prevents further motion in that direction. It allows the surgeon's skills and judgment to be combined with the precise constraints provided by the robot. Through, synergistic relationship of these two concepts, integrating human perception/cognition with machine manipulation, the accuracy and consistency of the robotic surgery can be improved.

GAZE-CONTINGENT MOTOR CHANNELING

Gaze-contingent information was enables information from eye movements and ocular vergence to be used in order to control the instruments and update the active constraints in dynamic surgical scenes. The work on gaze-contingent depth recovery was originally proposed by Mylonas et al.[38] Tracking the binocular eye movement and calculating ocular vergence, enables the 3D depth of the fixation point on the tissue can be determined. Given the known parameters of the calibrated stereo laparoscopic camera, the 3D distance between the laparoscopic instrument and the eye fixation point can then be computed. With this real time gaze-contingent framework able to augment robotic manipulation with human vision, the confidence and accuracy of the surgeon is infinitely improved.

FLEXIBLE TELEMANIPULATORS

Existing miniaturised master-slave instrument designs are generally unsuitable for following curved operation pathways where obstacle avoidance is critical. TO this end, flexible, snake-like manipulators have obvious advantages in cardiac surgery as they are not restricted to straight-line paths. They can navigate within lumens and confined spaces, and are able to move around obstructions to gain access easily to previously restricted areas. An intelligent flexible endoscope named the i-Snake (Imaging-Sensing Navigated And Kinematically Enhanced) has been developed which can naturally follow the contours of muscle planes. This is likely come into use for the common robotic cardiac surgeries such as revascularization, defibrillation and valve repair.

CONCLUSION

In summary, through its application and use in all of the above procedures, robotic cardiac surgery is rapidly growing in its use. Patient quality of care is improved by less tissue trauma and the absence of sternal bleeding, offering all of the advantages of minimally invasive surgery. For the surgeon, the true 3D visualisation, tremor elimination and multi-jointed, micro-instrumentation may produce excellent outcomes. Improvements in accuracy, largely through the introduction of augmented reality and perceptual docking as well as falling costs of robotic devices, will only improve techniques, promising sophisticated and innovative applications for robotics in future cardiac operations.

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