Quality of computer enhanced totally endoscopic coronary bypass graft anastomosis – comparison to conventional technique 1

V. Falk a,*, J.F. Gummert a, T. Walther a, M. Hayase b, G.J. Berry c, F.W. Mohr a

a The Department of Cardiac Surgery, Heartcenter, University of Leipzig, Leipzig, Germany
b Division of Cardiovascular Medicine, Stanford University School of Medicine, Stanford, CA, USA
c Department of Surgical Pathology, Stanford University School of Medicine, Stanford, CA, USA

Received 22 September 1998; received in revised form 10 November 1998; accepted 25 November 1998

Abstract

Objective: Aims of the study were to develop an endoscopic technique to perform robot assisted coronary anastomoses, using a computer enhanced telemanipulator and to compare the quality of the anastomoses with those performed using a standard open technique. Methods: A surgical telemanipulator with two instrument arms and a central videoscopic arm was used to perform remote endoscopic coronary artery bypass grafting on isolated porcine hearts. The end effectors and the videoscope were placed through three 10 mm port incisions. All anastomoses (Cx to LAD) were performed using a double armed 7–0 Prolene suture of 5 or 7 cm in length. All operations were performed remotely from the master console using ten times magnification, tremor filtering and 3:1 motion scaling. Initially 20 anastomoses were performed to develop and train the technique. Then, 20 robot-assisted anastomoses (group I) were compared with 20 anastomoses using a standard open parachute technique (group II). All anastomoses were checked for patency and leakage. Patency was confirmed by bench angiography. After fixation, all anastomoses were macroscopically evaluated for patency, intactness, alignment, intimal tears and dehiscence. Both angiographic and pathologic evaluations were performed with the examiners blinded to the technique of anastomosis. Results: In the initial feasibility series, time for anastomosis was 18.2 ± 9.1 min. All anastomoses were patent although minor stenoses were found in two and minor leakage was noted in five anastomoses. In the second series all anastomoses were patent, not leaking and showed a good run-off at angiography. Mean time for anastomosis in group I was 12.8 ± 2.4 min as compared with 6.3 ± 0.2 min in group II (P < 0.001), respectively. Macroscopic analysis demonstrated equal quality for both groups. There were no stenoses, no intimal tears and no dehiscences. All anastomoses had a normal alignment and intact suture lines. Conclusion: Using the Intuitive surgical telemanipulator, it is possible to remotely perform endoscopic coronary artery bypass grafting with the same quality as with an open standard technique after a brief learning curve. This will enable true endoscopic coronary artery bypass grafting with a precision that has not been achieved with any other previously applied endoscopic technique. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Robotic surgery; Coronary artery bypass graft surgery; Endoscopy

1. Introduction

Although various techniques have been developed to perform endoscopic coronary artery bypass grafting, the results to date have not been very encouraging [1,2]. The rigid design of conventional endoscopic instruments limits their intrathoracic mobility and thus their application in cardiac surgery. Long instrument shafts amplify tremors and make precise movements difficult. Working through a fixed incision point further impairs tissue manipulation (fulcrum effect). In addition, with only four degrees of freedom at the tip of the instrument, dexterity is markedly reduced. Suturing perpendicular to the shaft of the instrument (which is at some stage required when suturing an anastomosis) is therefore almost impossible [3,4]. In addition, image quality of the currently used videoscopes has not been adequate to perform precise suturing using 7–0 or 8–0 threads. Although higher in resolution, 2D images ren-
nder positioning of instruments inside the body more difficult due to the lack of stereoscopic depth [5]. Commercially available 3D systems however, have poor resolution and cause fatigue [6].

In order to overcome these shortcomings, surgical tele-manipulators have been introduced to cardiac surgery. The aim of the study was to develop a surgical technique to perform endoscopic coronary artery bypass grafting using computer enhanced robotic assistance. In addition, the quality of the anastomoses was compared with those performed using a conventional, open technique.

2. Methods

2.1. Description of the system

The system that was used for this study (Intuitive Surgical, Mountain View, CA) consists of a master console, control unit and a three arm surgical manipulator with fixed remote center kinematics [7]. The basic principle of the used robot is that of arm manipulators with a serial architecture of joints moved by electrically driven actuators. The surgeon is seated at the console and manipulates two master handles that represent the instruments. As the surgeon moves the manipulators at the console, the patient side manipulators follow the input motions on-line (Fig. 1). The video image gathered from inside the thorax is projected so it coincides with the workspace of the master manipulators. This overlap of master workspace and video image creates the visual illusion for the surgeon that his hands are holding onto tool tips inside the body. As a result, the surgeon manipulates the tools as though he was holding onto the instruments directly. Every motion of the handles is sensed by high resolution motion-sensors, processed and transferred to the surgical manipulators. These manipulators provide three degrees of freedom (pitch, jaw and insertion). The last element in this series is the surgical instrument also called end-effector. At the tip of the instruments, a cable driven mechanical wrist adds three more degrees of freedom (including roll) and one motion for tool actuation (i.e. grip). Grip torque of the end-effector (fine needle-holder) was programmed to 1.0 N. In order to enhance precision the system allows for scaling of the master-slave motion relation. Accordingly, a motion scale of 5:1 will move the tool 1 mm inside the chest for every 5 mm of motion at the master console. In this study, a motion scaling of 3:1 was used. In addition, unintended movements caused by tremor (human tremor occurs with a frequency of 6–10 Hz) are filtered by applying a 6 Hz motion filter. At any time, it is possible to temporarily disconnect the end-effectors from the master handles enabling repositioning of the master within its workspace, while the position of the instruments remained unchanged. A custom-made high resolution 3D-videoscope (with two three-chip charge coupled device (CCD) cameras) was used at a working distance of 4–5 cm from the surface of the heart.

2.2. Anastomotic technique and quality control

Isolated porcine hearts were placed in an endoscopic thoracic trainer after the Circumflex artery had been dis-
sected free and its side branches were ligated. All anastomoses (Cx to LAD) were performed using a double armed 7–0 Prolene suture of 5 or 7 cm in length. All operations were performed remotely from the surgical console using ten times magnification, tremor filtering and 3:1 motion scaling for all motions except roll. Initially, a two suture technique with one knot at the tip and one knot at the toe of the anastomosis was used. However, an open technique seemed preferable in terms of complete visualization, and a modified parachute technique was used after the first five hearts. The Cx-graft was placed beneath the LAD and rotated to 180° and the suture was placed underneath the graft. The near end of the suture was brought through the near side of the heel of the graft and then through the far side of the proximal end of the LAD. After four stitches the graft was approximated to the LAD and suturing was completed in a continuous fashion. After the initial feasibility study (20 anastomoses) the developed technique was compared in a second set of 20 robot-assisted (group I) with 20 anastomoses using a standard open parachute technique, performed on the bench with standard 3.5 magnifying loops and conventional instruments (group II). All anastomoses were checked for patency using coronary probes and for leakage by injecting saline at a pressure of 100 mm of mercury. Patency was confirmed by bench angiography using a mobile digital imaging system (OEC medical systems, Salt Lake City, UT). After fixation in 10% neutral, buffered formaline, all anastomoses were macroscopically evaluated for patency, intactness, alignment, intimal tears and dehiscence. Both angiographic and pathologic evaluations were performed with the examiners blinded for the technique of anastomosis. Time for anastomosis was calculated from the first needle contact to breaking the thread after finishing six knots.

The experiments were performed at the Intuitive Surgical research Laboratory. Angiographic studies and macroscopic evaluation were performed at the University of Stanford.

3. Results

In all cases operated with the telesurgical system, the anastomosis was performed totally endoscopically and completed without assistance. As the operator was seated in an ergonomically favorable position, fatigue did not occur. Repositioning of the master handles prevented uncomforta-ble or extreme hand positions. The high resolution provided by the stereoscope at 10× magnification provided a detailed view of the vascular structure. Depth perception was ade-quate and no inadvertent motions due to failed orientation occurred. The over-all stability of the system together with a 3:1 motion scale allowed precise suturing and non-traumatic tissue handling. In the initial feasibility series time for ana-stomosis was 18.2 ± 9.1 min. All anastomoses were patent although minor stenoses were found in two. In three cases, thread fractures occurred and required an additional suture.

Minor leakage was noted in five anastomoses during testing with saline at an injection pressure of 100 mm of mercury.

Mean time for anastomosis in group I was 12.8 ± 2.4 min as compared with 6.3 ± 0.2 min in group II (P < 0.001), respectively. No thread fractures occurred. All anastomoses were patent and there was no leakage (Table 1). All anasto-moses of both group I and II showed a optimal run-off at angiography (Fig. 2). There were no anastomotic obstructions visible at angiography. Macroscopic analysis demonstrat-ed equal quality for both groups. There were no stenoses, no intimal tears and no anastomotic dehiscences. All anastomoses had a normal alignment and intact suture lines (Fig. 3).

4. Discussion

Using the Intuitive surgical telemanipulator, it is possible to remotely perform endoscopic coronary anastomoses with the same quality as with an open standard technique. After an initial learning curve, a convenient suturing technique was developed. The described technique resembles an open parachute suturing technique with the advantage of optimal visualization and the use of a running suture. As a consequence, high quality anastomosis with no evidence of intimal injury and normal intimal alignment could be performed. More important, with an average time of only 12 min per anastomosis, endoscopic bypass grafting is possible in a tolerable time frame for the first time. Although still more time consuming than a conventional surgical technique, the results are in clear contrast to the 45 min per anasto-mosis reported in other studies using endoscopic instruments [1,2].

A different telesurgical system (Zeus-System, Computer Motion, Goleta, CA) has recently been evaluated in a plastic model for coronary anastomoses. Using this system, it was possible to create patent anastomoses between plastic tubes using a 7–0 monofilament running suture at an aver-age time of 46 ± 12 min [8]. The Zeus-system consists of three independent arms that can be freely mounted on the operating table and interact through a microprocessor. The camera arm is voice controlled while the instrument holding arms are triggered by operating the master manipulator han-

<table>
<thead>
<tr>
<th></th>
<th>Group I</th>
<th>Group II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intactness of anastomosis</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Correct alignment</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Dehiscence</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Intimal tears</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Intactness of sutures</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Patent lumen</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
bles from the console, where a 2D or 3D videoscopic image is displayed. Although the concept is also that of a master-slave architecture, the end-effectors have only four degrees of freedom. It has been well-documented, that effectors with different dexterity complete a task with a given index of difficulty at a different time. This time difference is directly related to the dexterity of the system. Dexterity of anthropomorphic robots can be defined by the number of dof multiplied by frequency and divided by the resolution [9]. As the number of dof is in the nominator of this equation for dexterity, six dof will theoretically enhance dexterity by a factor of 1.5 as compared with a four dof system. This may explain in part, that the time required to perform an anastomosis using the Zeus system that provides four dof only exceeds that of the six dof system used in this study. The use of telepresence surgery systems with four dof has also been shown to be associated with longer operating times for gastrotomy closures and arteriotomy closures [10,11].

Other factors are of equal importance for the evaluation of telemamipulators. The system has to be safe and may not produce inadvertent motions [12]. During the study the system worked safely and no technical mishaps occurred. Remote computer enhanced surgery is based on the concept of telepresence surgery. The surgeon no longer manipulates the tissue directly, but acts via a human-machine interface using surgical manipulators from a remote location. In its current form, telepresence surgery goes along with a loss of tactile feedback. The texture of the tissue that is manipulated and the forces that are exerted on the tissue can not be felt at the master console (except for massive tissue contact (inside body forces, i.e. bony resistance) as well as external forces (collision of slaves that are transmitted to the master)). This was reflected in the number of thread fractures in our feasibility study. Concern has been raised whether the inability to physically touch the tissue may eventually cause injury. Improvement of the human-machine interface implementing a haptic interface that provides tactile and force feedback will possibly improve the manipulation of tissue and thin threads. According to Madhani however, forces beyond 0.4 N cannot be felt. While a displacement of soft tissue of 6 mm will only create forces of 0.2–0.6 N and therefore can hardly be felt, a 1 mm displacement of tissue can already be seen. It is therefore debatable if force reflection is indeed required or if high image quality will visually compensate for the loss of tactile feedback [13].

Customized suture material is necessary in order to perform coronary anastomoses. A double armed 7–0 suture of
References for their help in preparing the hearts.

Acknowledgements

The authors thank Mrs. J. Mc Loughlin and K. Gummert for their help in preparing the hearts.

References


Appendix A. Conference discussion

Dr F. Benetti (Santa Fe, Argentina): I don’t have any doubt that this is the way to go I think in trying to do this coronary surgery in an ambulatory fashion. I have a concern in using this equipment in the beating heart, probably it will be in the future, and it will be very interesting to try to achieve this goal of doing this coronary surgery ambulatory. One of my concerns is that, probably the semi-robotic arm in helping the surgeon on the table, will be an interesting intermediary step before you can apply this kind of technology to use in the beating heart. That’s my only concern. The other aspect I want to comment on is that probably the saphenous approach will be the best approach to using this in the beating heart.

Dr Falk: It was not our intention to work on the beating heart in the beginning. I think that if we can develop a stabilization mechanism that can be applied endoscopically, from a technical point of view, then the anastomosis can be done endoscopically. To my knowledge, this is the first time, that we have a system available that gives us this possibility. All recently published studies working on endoscopic bypass surgery showed that it takes at least almost 30–45 min to perform an anastomosis and the 5–7cm length seems to be ideal. Longer sutures are difficult to handle, due to the small field of view when working under high magnification. Suture material with less or no memory but increased strength is desirable.

Two categories of robots are currently being used for surgical applications. Off-line systems, that are used in orthopedics to preshape the femur for total hip replacement are pre-programmed robots for a specific task which is then performed autonomously [14]. Cardiac surgical applications, in contrast, require on-line systems with the operator in steady control of the system (which is then called a manipulator rather than a robot [15]) via a human-machine interface. Although very attractive, the concept of virtual immobilization of the beating heart would at least temporarily violate this principle, as the system has to correct any motion performed at the console according to the actual position of the heart autonomously.

Our study was performed on an arrested heart. Given the high quality and the short time necessary to perform an anastomosis, it seems possible to also perform a computer enhanced endoscopic anastomosis on the beating heart if endoscopic stabilizers become available.

The search for new anastomotic devices was stimulated by the poor results of conventional endoscopic suturing. These devices may enable a different endoscopic approach. However, with any one-shot device ( stapling or suturing) it will be difficult to deal with an asymmetric and partially calcified arterial wall, as no individual attachments between the graft and the target vessel are possible. In contrast, computer enhanced suturing combines the quality of an open suturing technique, where every stitch can be planned and adjusted to the local vessel morphology with high precision in an endoscopic environment.

In conclusion, the Intuitive system allows endoscopic suturing of coronary anastomoses in a time frame that makes this method a promising technique also for beating heart applications. No special surgical technique is required to operate the system, as all movements are readily and naturally transferred to the tip of the instruments. Using the mechanical wrist, it is easily possible to suture along a line perpendicular to the shaft, which is virtually impossible using rigid endoscopic instruments. In addition, motion scaling and tremor filtering the system provides ambidexterity which facilitates surgical strategy.
quality of these anastomoses is poor. I think we could show that with this technique, the anastomosis can be done in a time that allows for beating heart surgery. Performance of the anastomosis takes 10–15 min now, and we know from our MID CAB experience that the LAD can be safely occluded for this period of time. So I think it is only a matter of having an endoscopic stabilizer that will allow to stabilize the heart enough, to perform a beating heart endoscopic coronary anastomosis.

Dr F. Mohr (Leipzig, Germany): I think you are right with the sub-xiphoid approach, and actually Dr. Falk is already working on that experimentally, following your suggestion.