

Optimization of Vessel Orientation for Robotic Coronary Artery Bypass Grafting

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ABSTRACT

The availability of telemanipulation robots has not yet resulted in the emergence of a reliable endoscopic coronary bypass procedure. A major challenge in performing a closed-chest coronary operation is creating a high-quality anastomosis in a reasonable period of time. In this experimental study, the impact of distal vessel orientation on the speed and accuracy of anastomosis was quantified. We found that vessel orientation and the relative angle of the surgical plane influence anastomosis speed, the trauma to the vessel, the accuracy of stitch placement, and the eventual achievement of hemostasis. Our results suggest that the speed and accuracy of a robotically performed anastomosis of a vessel graft to a coronary artery can be improved by making small changes in vessel orientation. Vessels should be positioned between the horizontal and diagonal orientation and inclined between the horizontal and +45°. Because the 6-o'clock stitch is particularly challenging, surgeons may benefit from an orientation that moves the heel or the toe of the anastomosis away from this critical position.

INTRODUCTION

Trends in cardiothoracic surgery have aimed at minimizing incisions and surgical trauma [Talwalkar 1998, Reichenspurner 1999a, Duhaylongsod 2000]. Computer-enhanced telemanipulation robots, such as the Zeus (Computer Motion, Santa Barbara, CA, USA) and the da Vinci (Intuitive Surgical, Mountain View, CA, USA), have enabled surgeons to perform closed-chest, totally endoscopic procedures [Boyd 2000, Kappert 2000], but the method is far from satisfactory and is not gaining much momentum.

One major challenge in performing a closed-chest coro-

nary operation is creating a high-quality anastomosis in a reasonable period of time. Although distal anastomotic devices have promise for the future, major challenges—the technical challenge of dealing with small atherosclerotic vessels and the biological challenge of restenosis—remain to be overcome. At present, the sewn anastomosis is the gold standard for optimal flow [Reichenspurner 1999b] and for intermediate and long-term patency.

In robotic endoscopic coronary artery bypass grafting (CABG), the anastomosis of the left internal mammary artery (LIMA) to the left anterior descending artery (LAD) has been studied almost exclusively because these vessels are the most accessible and easiest to expose from the left chest. Unfortunately, most patients who present for bypass surgery have multivessel disease, and the problem of anastomosis to vessels other than the LAD significantly adds to the challenge. In a previous report we discussed how the use of endoscopic proximal anastomoses and cardiopulmonary bypass were useful adjuncts to the goal of closed-chest multivessel CABG. In this report, we consider the issue of vessel orientation and how the trajectory of the distal vessel in the endoscopic field affects the outcome of a robotically sutured anastomosis.

We found that vessel orientation and the relative angle of the surgical plane influence the speed of the anastomosis, the trauma to the vessel, the accuracy of stitch placement, and, consequentially, the eventual achievement of hemostasis. Using an experimental model, we sought to determine the ideal orientation for a target vessel.

MATERIALS AND METHODS

Simulation of the Anastomosis

Using the Zeus robotic interface and the CardioView (Vista, Westborough, MA, USA) stereoscopic head mounted display, a group of 5 cardiac surgeons were asked to perform a sewing exercise.

A 2-in segment of polytetrafluoroethylene (PTFE) tubing (Edwards Lifesciences, Midvale, UT, USA), with an inner diameter of $\frac{3}{16}$ in and an outer diameter of $\frac{1}{4}$ in was prepared by punching out an oval-shaped hole ($6 \text{ mm} \times 3 \text{ mm}$) through 1 wall. Ten equally spaced marks were placed along the perimeter of the opening (3 marks at the heel, 3 at the toe, and 2 pairs in between), each approximately 1.25 mm from the edge. The segment of tubing was then fitted to a stand to

Received May 14, 2004; received in revised form July 30, 2004; accepted August 19, 2004.

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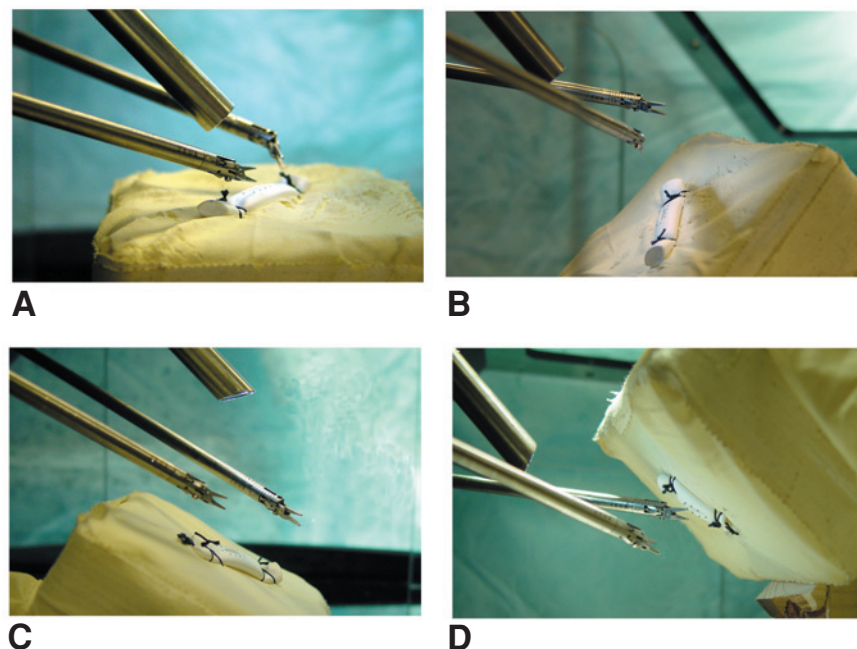


Figure 1. Experimental setup. The thoracoscope was locked at a 45° elevation and a left chest approach to several vessels was simulated. A, The anastomosis of the left internal mammary artery to the distal left anterior descending coronary artery (LAD) was performed with the plane level and the vessel presented either diagonally (shown here), horizontally, or vertically relative to the camera. B, An anastomosis to the proximal LAD was simulated with the +45° plane and conducted with the 0° scope. C, The -45° plane, representing the course of the right coronary artery, was undertaken with the 30° thoracoscope. D, The 135° plane, performed with the 30° scope, simulated a left-chest approach to the circumflex artery and was the most challenging plane.

incline the operating plane and placed in the acrylic plastic (Plexiglas) trainer (Computer Motion). We built 4 stands: a 0° (horizontal) plane to simulate the anastomosis of the LIMA to the distal LAD, a +45° plane to approximate the plane of the proximal LAD, a -45° plane to simulate the right coronary artery, and a 135° plane to model the position of the circumflex artery as viewed from a left chest approach (Figure 1).

A CV-8 double-arm Gore-Tex suture (W. L. Gore and Associates, Flagstaff, AZ, USA) was sutured circumferentially around the opening in the graft, starting at 1 of the marks chosen at the surgeon's preference. Each stitch was taken from the inside to the outside of the vessel, and the surgeon was allowed to start and end at any position and to switch sewing directions, provided that no bite was skipped. A final knot with 3 throws was performed to complete the anastomosis (Video online). With the exception of the zoom control, the surgeon could not alter the position of the thoracoscope, which was set at a 45° angle relative to horizontal.

In the first set of experiments, the operating plane was horizontal, and the surgeon was given in random order 3 orientations of the vessel on which to sew. The vessel was presented straight horizontally, straight vertically, or diagonally (Figure 2).

The second set of experiments involved tilting the operating plane to +45°, -45°, and 135° from the horizontal position. For each of these 3 positions, the vessel was mounted diagonally, and the camera position remained at 45° from horizontal. Experiments were conducted with a 0° endoscope (10 mm, 35 cm in length; Carl Zeiss, Göttingen, Germany) or with a 30° endoscope when the blocks were tilted to -45° or 135°.

Data Gathering

Each sewing exercise was recorded on videocassette to facilitate data collection. Total time was measured from the moment the suture was first touched to the final throw of the second knot. The time spent performing knots was recorded separately. Each bite of the anastomosis was individually timed to reflect the time spent setting up the needle in the needle driver and the time needed to actually take the bite. The number of "fumbles," such as having to retake the bite, breaking the suture, or dropping the needle, was also recorded for each suture placement.

One of the authors examined each stitch with a 40× dissecting microscope and graded it for accuracy and trauma to the PTFE tubing (Table). The needles were examined under 40× magnification for any deformations or kinks. The entire anastomosis was observed under 25× magnification and given an overall quality grade based on the spacing of the bites, their radial orientation, and any deformation in the geometry of the opening in the graft (Figure 3). The conduit was subsequently split open from the back wall, and the anastomosis was inspected for technical errors.

Data Analysis

The data were entered into a spreadsheet (Excel; Microsoft, Redmond, WA, USA), and a score for each stitch was calculated on the basis of the bite's accuracy, trauma, and the number of fumbles, with each of these components carrying equal weight. The total score, graded relative to a maximum of 100 points, was calculated from the weighted average of

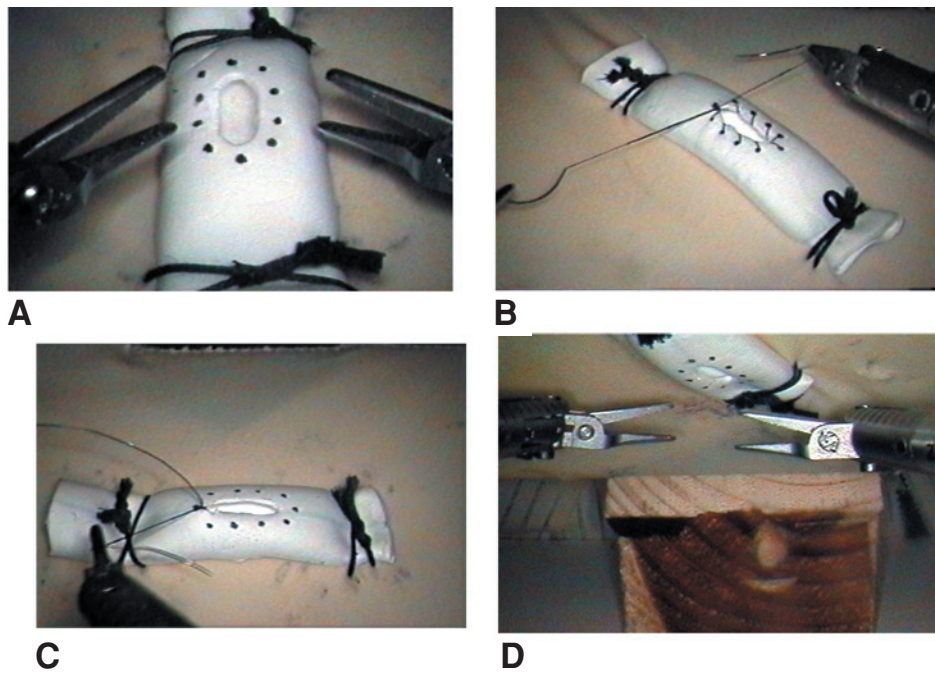


Figure 2. Appearance of the target vessel through the operative scope. Clockwise from top right, the first 3 images were taken with the vessel mounted on a horizontal plane, which is representative of an anterior target vessel. A, The vertical vessel orientation prior to commencing the anastomosis. B, The final knot is being tied on an anastomosis presented diagonally. C, Completion of the anchoring knot prior to sewing the anastomosis on a vessel oriented horizontally. D, Surgeon's view of a simulated left-chest approach to the circumflex artery (135° plane).

the sum of scores obtained from each of the 10 bites (80%), the needle trauma score (10%), and the overall quality score (10%). A 10% penalty was deducted for each gross error. The relative time for each stitch, which was calculated by dividing the absolute time required to take a particular bite by the total time required to take all bites, eliminated the effects of intersurgeon variability. Statistical analysis was conducted with the SAS program (SAS Institute, Cary, NC, USA). In general, a P level of $<.05$ was considered statistically significant, but given the relatively small sample size ($n = 6$), we also report a P level of $<.10$ as potentially significant.

RESULTS

With the surgical plane horizontal and the camera placed at a 45° elevation, the orientation of the target vessel was changed among 3 different angles.

Effects of Vessel Orientation

Placing the vessel in a diagonal orientation significantly reduced the total time required to perform the anastomosis (1013 ± 119 seconds) compared with the vertical presentation (1222 ± 197 seconds; $P < .1$) or horizontal placement (1101 ± 119 seconds; difference not statistically significant) (Figure 4). In addition, the time required for making the initial and final knots took significantly longer when the vessel was presented vertically (469 ± 95 seconds) than when it rested horizontally (314 ± 50 seconds; $P < .05$) or diagonally (317 ± 51 seconds; $P < .05$).

Performance also depended on the orientation of the target vessel. Placing the vessel in a vertical orientation resulted

in higher rates of fumbles, significantly increased trauma, and decreased accuracy compared with the diagonal presentation. Needle deformation was also significantly worse ($P < .05$) for the vertical group (4.2 ± 1.2) than for the horizontal (2.3 ± 1.4) or diagonal (2.1 ± 0.9) group. The overall quality of the anastomoses in the vertical group markedly lagged behind that of the other 2 groups.

Of the 6 trials performed for any given orientation, 3 of the vertical anastomoses (50%), 2 of the horizontal anastomoses (33%), and 1 of the diagonal anastomoses (16%) contained 1 or more gross errors. Eighteen anastomoses were sewn in the horizontal plane. Ten gross errors were scored. Six were due to intraluminal crossovers of the suture, and the other errors comprised a rip in the anchoring knot, a faulty last knot, a stitch not coming all the way through, and a suture breaking while a stitch was being placed. One surgeon accounted for 6 of the gross errors, whereas the other surgeons incurred 1 or no gross errors.

The total score for the anastomosis was significantly lower when the vessel was oriented vertically than when it was in the diagonal ($P < .05$) or horizontal orientation.

Bite Analysis

An analysis was performed for the bites around the anastomosis. Bites taken in the 6-o'clock position took significantly longer to execute, both on an absolute basis and when corrected for intersurgeon speed variations, and produced quality scores that were significantly lower ($P < .05$) compared with adjacent bites located at the 5- and 7-o'clock positions. This finding was also true to a lesser extent for bites at the 8-o'clock position, which showed statistically worse

Scoring Criteria

	Score
Fumbles	
• Breaking the suture	
• Dropping the needle	
• Retaking the stitch after piercing the vessel	
• Reloading or changing the position of the needle in the driver after attempting a bite	
• Placing forces so large that they caused the block to slide	
• Passing the needle between instruments more than 4 times without attempting a bite	
No fumbles	0
1-2 Fumbles	1
3-4 Fumbles	2
≥5 Fumbles	3
Trauma	
Hole in vessel approximately size of suture	0
Slightly larger suture size (<0.2 mm)	1
Larger hole (≥0.2 mm)	2
Frank rip	3
Accuracy	
On mark or <.5 mm	3
0.5-0.8 mm from center of mark	2
0.8-1 mm from center of mark	1
>1 mm from center of mark	0
Needle score	
Needle broken	5
Totally deformed (≥2 kinks)	4
One kink (abrupt deformation at a specific point on needle) at tip or body	3
Bent tip or body (change in overall curve of needle but not at any specific point on the needle)	2
Slight bend visible only under magnification	1
No appreciable change in shape of needle	0
Overall quality	
All bites are on marks and well spaced	5
All bites are radial, but not all on marks or well spaced	4
Most bites are radial	3
Anastomosis is completed; ostomy remains oval in shape	2
Anastomosis is completed; ostomy is deformed (ie, too much tension on suture or it rips)	1
Anastomosis is not completed	0
Gross error	
• Inability to tie knot with 3 throws	
• Suture crossing in vessel	
• Doubling back of suture	
• Suture not going all the way through vessel wall	
• Suture break during sewing	
• Skipping a stitch	
• Not bringing the 2 ends of the suture at the same location before tying final knot	
Bite score*	
Score = Accuracy + (3 – Trauma Score) + (3 – Fumble Score). Maximum bite score is 9.	

Continued

Table Continued

Total Score†

$$TotalScore = \sum_{i=1}^{10} (BiteScores_i) + \sum_{j=1}^3 (5 - NeedleTrauma_j) + (2 \times OverallQuality) - (10 \times GrossErrors)$$

*A bite score was calculated for each stitch.

†A total score was derived for the anastomosis. The total score for the anastomosis is graded to a maximum of 100 points. A 10-point penalty is incurred for each gross error.

scores and accuracy and required more time to perform compared with the adjacent 9-o'clock bite (Figure 5).

Detailed Analysis of the 6-O'Clock Position

The 6-o'clock position was analyzed to determine the effects of vessel orientation on the performance of this stitch (Figure 6). The data demonstrated that as the angle of vessel orientation is increased from the horizontal position, the results for all measured parameters worsened uniformly. At the 6-o'clock position, the vertical vessel orientation had a significantly poorer time ($P < .05$), relative time ($P < .05$), and score ($P < .05$) compared with the horizontal position, and the vertical orientation had the poorest overall results for number of fumbles, trauma, and accuracy.

Sewing Approach

Sewing around an opening in the graft with a robotic interface allows surgeons to perform bites in 4 ways because forehand and backhand approaches can be taken from either the right or left needle driver. The data indicated that the left forehand approach was favored from the 3-o'clock to the 5-o'clock position, whereas a right forehand technique was predominantly selected from the 6-o'clock to the 9-o'clock position. Some stitches, such as at the 2-, 6-, 10- and 12-o'clock positions, could be performed in more than 1 way and could produce different results (Figure 7).

Effects of Angle of Operative Plane on Performance

Five surgeons were tested at each of the 4 angles at which the target vessel's plane was tilted: -45° (away from the instruments), horizontal, $+45^\circ$, and 135° (Figure 8). The total time needed to perform the anastomosis was lowest in the $+45^\circ$ and horizontal groups and was significantly higher ($P < .05$) for the 135° anastomosis. Examination of the time necessary to sew around the ostomy showed that the $+45^\circ$ anastomosis required less time to perform than the horizontal anastomosis ($P < .05$), which in turn was faster than the anastomosis in the 135° plane ($P < .05$). The times needed to tie knots were longer in the 135° ($P < .05$) and the -45° ($P < .1$) groups than in the horizontal plane, which took the least time.

With the exception of the $+45^\circ$ group, which had a significantly reduced level of trauma to the target vessel ($P < .05$), all other planes produced similar results. The average bite accuracy was lower ($P < .05$) when the plane was tilted at 135° than for all other angles. Fumbles were highest in the 135° group and lowest for the $+45^\circ$ group ($P < .05$).

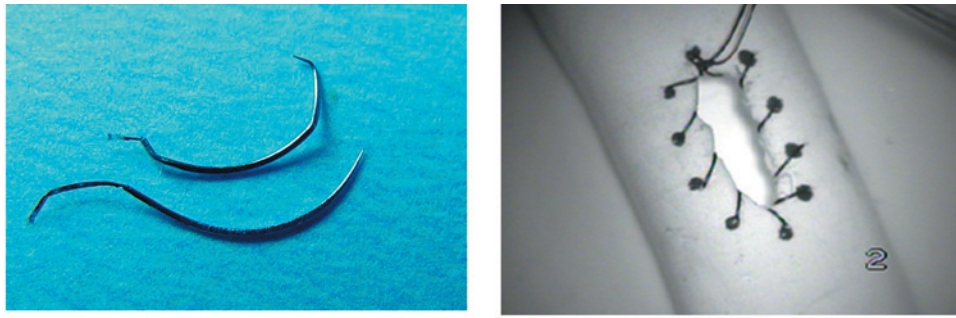


Figure 3. Grading the anastomosis. Left, The bottom needle retained its original shape, but the top needle became deformed and kinked. Right, Example of an anastomosis with an ideal score of overall quality. Each of the bites is radial and accurate, there are no signs of trauma around any stitch, and the ostomy is not deformed.

The average score, representing the sum of the bite scores, was higher in the $+45^\circ$ group ($P < .05$) than in the horizontal group, which in turn was superior to the 135° group ($P < .1$). Needle trauma was highest in the -45° group ($P < .05$), whereas the other angles exhibited comparable results. The overall quality of the anastomosis was lower ($P < .1$) in the 135° plane. Of the 5 anastomoses performed at each angle, 2 in the -45° group, 1 in the horizontal group, 0 in the $+45^\circ$ group, and 3 in the 135° group contained 1 or more gross errors.

The analysis of individual bites showed that the 10-o'clock stitch situated at the toe in the 135° plane was significantly the most challenging in terms of fumbles, trauma, relative time, and score ($P < .05$ relative to the average over all bites).

Surgical Experience

The effects of surgical experience (such as the number of years as a surgeon and the number of human CABG procedures performed) and robotic experience (in terms of the hours spent with the Zeus system) were correlated with the scores and times measured during the sewing exercise. No variables representing career duration or prior experience with robotic surgery were predictive of performance (an observation that was depressing to our senior surgeons).

DISCUSSION

Effects of Vessel Orientation

The 3 orientations of the target vessel were presented in

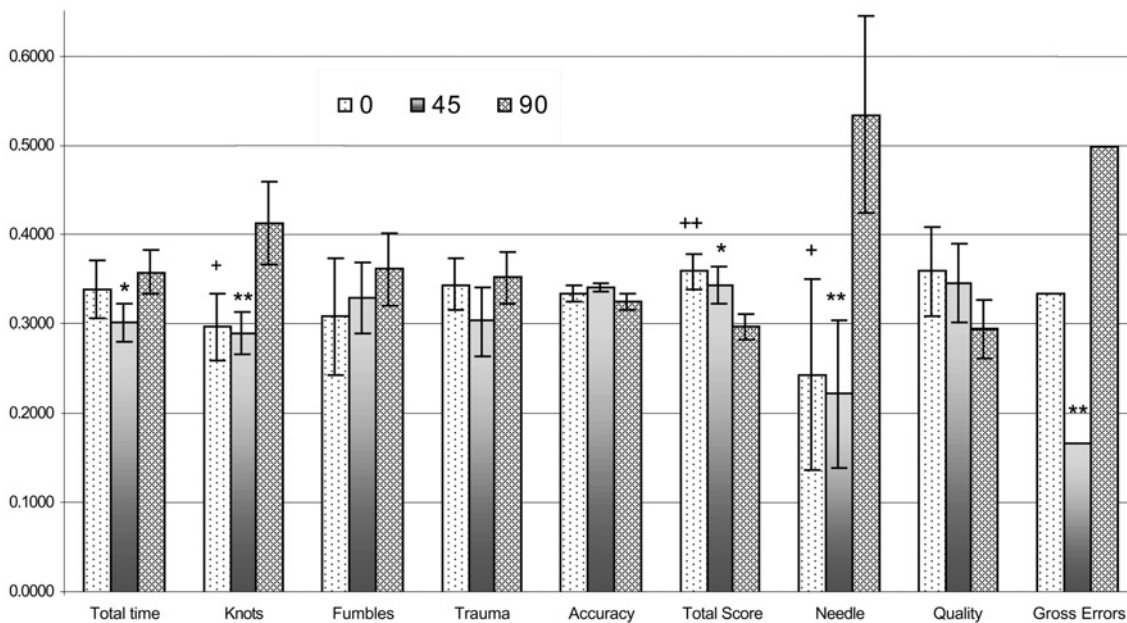


Figure 4. Effect of vessel orientation on performance of the anastomosis ($n = 6$). Total time needed to complete the anastomosis and the time required for initial and final knots (Knots) demonstrated that sewing a vertical anastomosis required a significantly longer time. Total Score and Gross Errors reflected the significant difficulty in sewing the vertical (90°) anastomosis. Error bars indicate 70% confidence interval. Asterisks denote statistical significance between diagonal (45°) and vertical groups (*, $P < .10$; **, $P < .05$); crosses denote statistical significance between horizontal (0°) and vertical groups (+, $P < .10$; ++, $P < .05$).

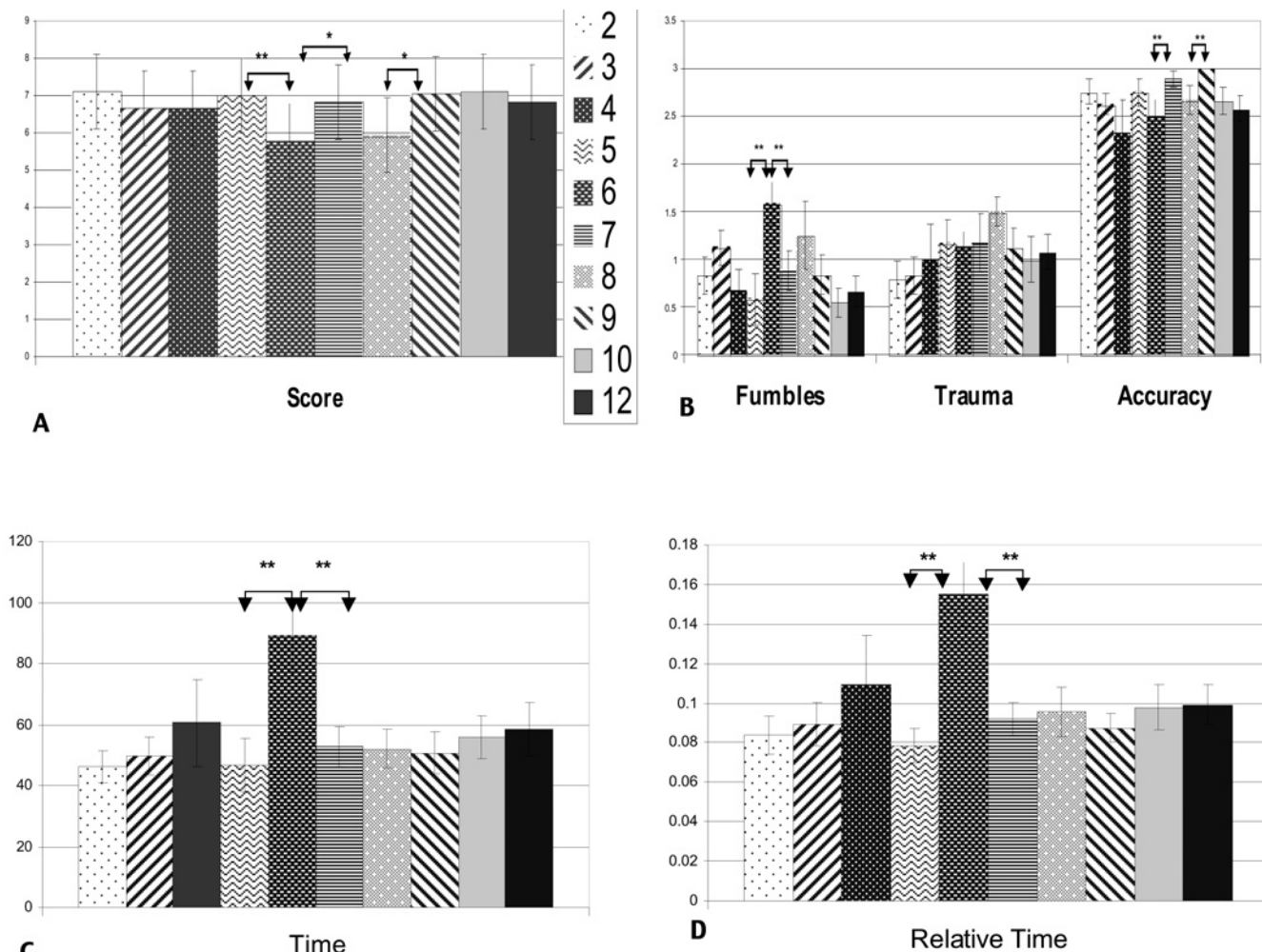


Figure 5. Analysis of performance for each of the bites around the anastomosis ($n = 180$). The 6-o'clock stitch produced lower bite scores (A), resulted in a significant excess of fumbles and below-average marks for accuracy (B), and required a significantly longer time to perform (C and D) than the adjacent 5- and 7-o'clock bites (numbers indicate position on a clock face). To a lesser extent, the 8-o'clock stitch had a lower bite score (A), higher trauma, and significantly lower accuracy (B) than the flanking 9-o'clock position. Error bars indicate the 70% confidence interval (*, $P < .1$; **, $P < .05$).

random order to eliminate the effects of a learning curve. The data demonstrated that vessel orientation had a statistically significant effect on time-independent parameters as well as on the speed for the performance of the anastomosis. Orientation between the horizontal and diagonal directions was preferable to the vertical positioning. This conclusion corresponded with the surgeons' subjective impressions regarding the level of difficulty. As either their first or second choice, 4 of the 6 surgeons preferred the diagonal position, 2 favored the horizontal orientation, and none picked the vertical anastomosis.

Although the other results for the horizontal and diagonal orientations were statistically similar, there was a significant difference between the diagonal and vertical orientations in the total time required to perform an anastomosis. The time spent tying knots was significantly longer in the vertical group than in the other 2 groups because the needle drivers in the vertical orientation tended to cross the camera's line of sight and obstruct the field of view. In addition, when the ves-

sel was oriented vertically, the amount of suture left over for tying the final knot was slightly shorter because surgeons tended not to pull the slack out as much. The higher number of fumbles and the consequent need to reload the needle in the driver multiple times also contributed to increased times in the vertical group.

The total score was significantly lower in the vertical group. Although the increased number of fumbles and incidence of trauma had an impact, this difference was mainly caused by decreased overall quality, increased needle trauma, and rates of gross errors. More of the ostomy's perimeter faced the camera in the horizontal and diagonal angles than in the vertical orientation, thus facilitating the placement of stitches. By better appreciating the path required to take the bite, the surgeons reduced the "side forces" and avoided trauma to both the vessel and the needle. Accuracies were statistically similar in all 3 groups because accuracy tended to reflect the surgeon's determination to hit the target, even at

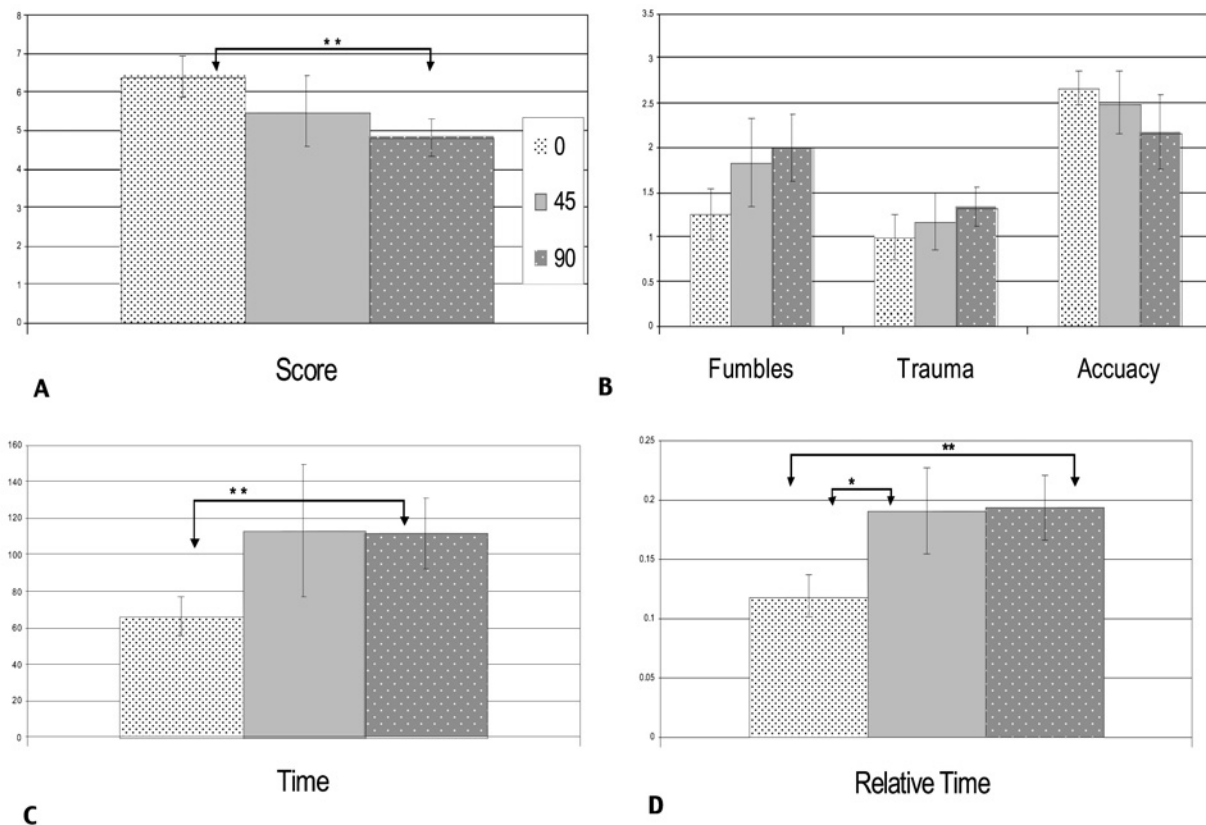


Figure 6. Analysis of the 6-o'clock stitch as a function of vessel orientation. Rotating the vessel away from the horizontal position ($n = 12$), past the diagonal alignment ($n = 6$), and toward the vertical orientation ($n = 6$) results in a consistent decline in performance of the 6-o'clock stitch (A). Every measured parameter is affected uniformly (B). Both absolute (C) and relative (D) times needed to perform this stitch deteriorated in a statistically significant manner. Error bars reflect the 70% confidence interval (*, $P < .1$; **, $P < .05$).

the cost of several attempts or increased trauma.

Orienting a vessel horizontally or diagonally resulted in widening the dimensions of the surgical target area. The increase in the ostomy's aspect ratio (width) compared with that in the vertical position improved visualization (because instruments obstructed the field of view less often) and dexterity. These factors helped decrease the number of gross errors and improve the quality score, an indirect reflection of hemostatic integrity obtained by measuring the radial orientation and evenness of the bites along the ostomy.

Challenges at the 6-O'Clock Position

To further explain the differences between the 3 orientations, we undertook a detailed analysis of each of the bites around the anastomosis. The 6-o'clock stitch was most sensitive to vessel orientation, required a significantly longer time, and produced poorer results than other stitches because of limitations on the robotic needle drivers. The "straight down" bite was executed by positioning the microwrist at its maximum angular deflection relative to the instrument's shaft, making it difficult for the needle tip to describe a smooth arc while sewing. Allowing the wrist to travel a full 90° relative to the instrument's shaft and allowing free rotation about the wrist through an additional degree of freedom

could potentially improve the kinematics of the needle. Potentially, a "fly by wire" system could process the surgeon's input from the robotic console to optimize the kinematics of the needle tip for the most complex bites.

Because our data as well as the physicians' subjective feedback indicated that the 6-o'clock position was the most challenging, it behooves the surgeon to orient the vessel to avoid placing the heel or the toe of the anastomosis in this position. Our analysis of the 6-o'clock position as a function of vessel orientation confirmed that vertical vessel placement was a poor choice by virtue of having the 6-o'clock position at the anastomosis toe. We noticed that as the angle of vessel presentation decreased, the values of all measured parameters, including times, were ameliorated. A possible explanation is that there was little lateral room at the toe to take the difficult vertical bite. The lateral room was greater in the 0° and 45° orientations, thus facilitating the execution of the bite and improving all measured parameters.

The adjacent positions, namely the 5- and 7-o'clock positions, showed excellent results and resulted in few fumbles, and the bites were relatively quick to take. This observation would justify the development of a device that could be introduced through a port and alter the direction of a target vessel on the surface of the heart in a fashion similar to that of a sta-

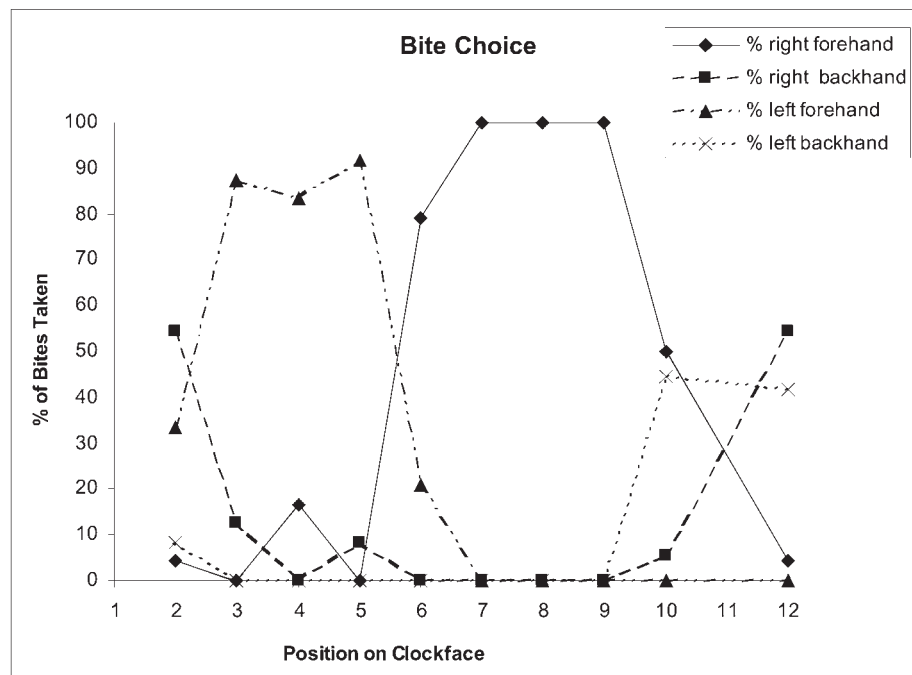


Figure 7. Sewing approaches (left or right, and forehand versus backhand) as a function of position around the anastomosis when the target vessel lies on a horizontal plane. The vertical axis indicates the percentage of observations in which the particular approach was used. The horizontal axis represents the orientation given as the position on a clock face. Bites taken at 10-, 12-, 2-, and 6-o'clock positions could be performed by 2 different approaches. At the 2-o'clock position, the left forehand approach showed a significantly superior bite accuracy ($P < .1$) and a slight speed advantage over the right backhand approach, whereas the right forehand approach was significantly quicker at the 6-o'clock position than the left forehand approach ($P < .1$). A left backhand approach at the 10-o'clock site was significantly faster than a right forehand approach ($P < .05$). At the 12-o'clock position, there was no statistically significant difference between the left and right backhand approaches.

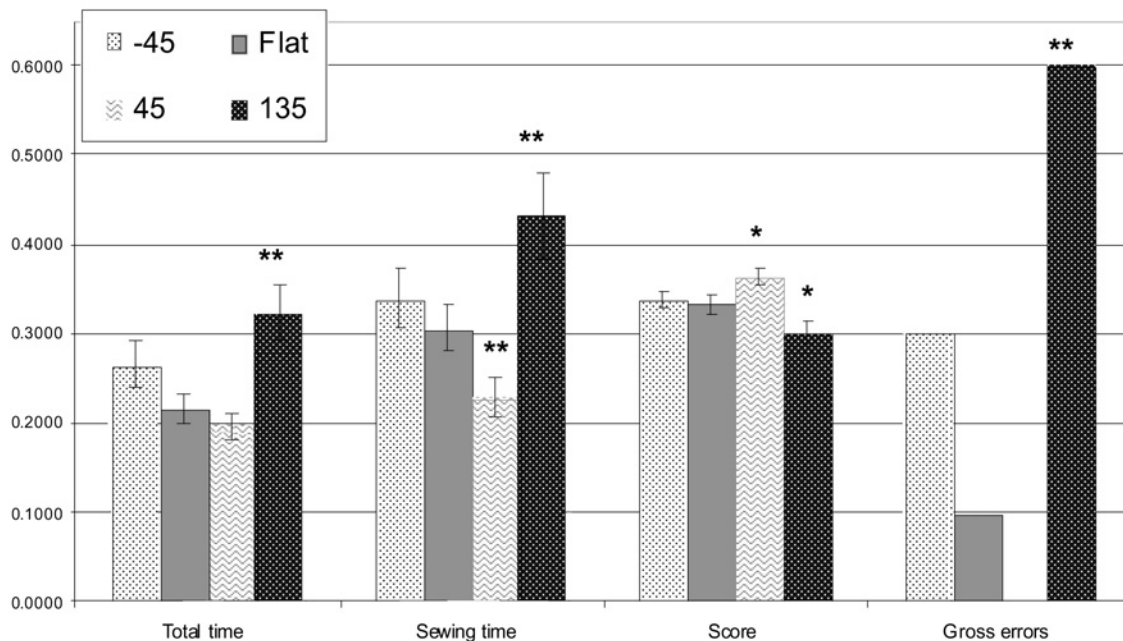


Figure 8. Effect of angle of operative plane on the performance of the anastomosis ($n = 5$). The $+45^\circ$ incline necessitated less time to sew around the anastomosis, exhibited a higher score, and had 0 gross errors compared with the level plane, which had a single error. The 135° group took significantly longer, yielded a lower score, and generated 6 gross errors. The plane oriented at -45° took significantly longer to sew than the flat plane and produced 3 gross errors. The error bars represent the 70% confidence interval. Asterisks indicate statistical significance (*, $P < .1$; **, $P < .05$) relative to the horizontal group.

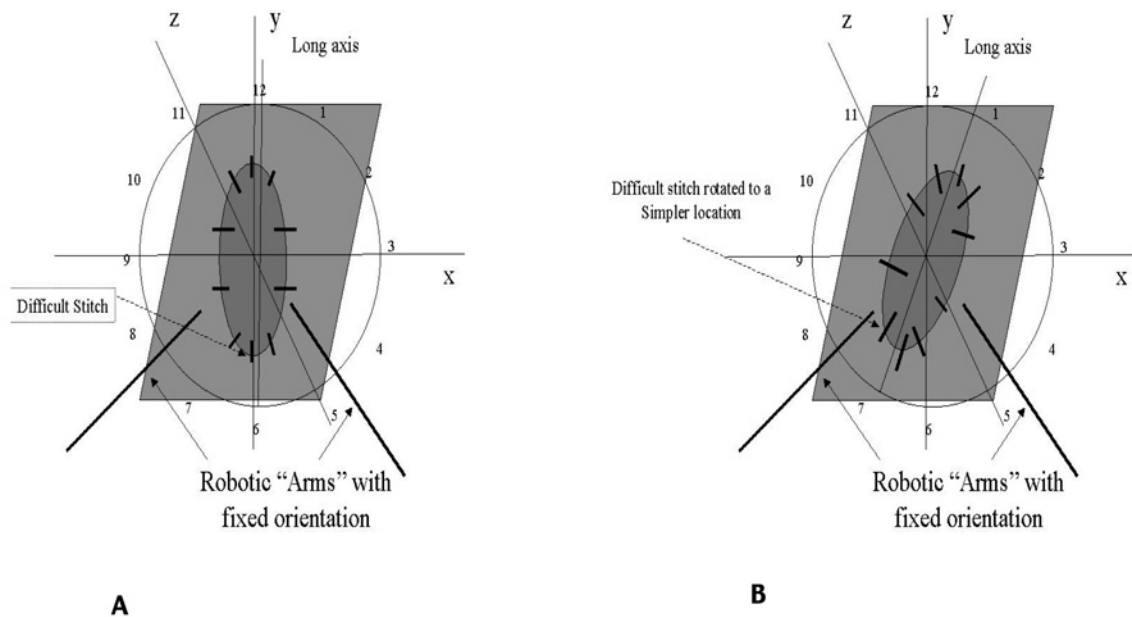


Figure 9. Concept of an endoscopic manipulator. Challenging bites (eg, 6-o'clock position, illustrated here) are significantly more difficult to execute than adjacent stitches (A), especially at the heel or toe of an anastomosis. An endoscopic manipulator could be used to rotate the target vessel and simplify the placement of a particular stitch (B). This device may also be capable of altering the plane of the target vessel and further facilitate the performance of multivessel coronary artery bypass grafting.

bilizer (Figure 9). A 30° rotation of the target vessel relative to the instrument plane would greatly simplify taking challenging bites, such as at the 6- and 8-o'clock orientations.

Performance of a Well-Sewn Anastomosis

Techniques for robotic surgery are different from those for conventional surgery. Our data support this observation by demonstrating a lack of correlation between surgical experience and predicted score. Surgeons need to learn new techniques that go against conventional training. This study demonstrated that learning to sew with both hands and even using left backhand techniques are efficient and accurate when used properly. This observation might be explained by limitations in the microwrist-equipped needle drivers, the requirement to optimize vision through the scope, and the constraints imposed by a restricted number of degrees of freedom.

Surgeons are able to intuitively select the ideal approach for most bites. However, the 10-, 12-, and 2-o'clock positions, as well as the 6-o'clock positions, were approached by means of 2 or more methods because the 12- and 6-o'clock positions may be approached from either side with a backhand or a forehand approach, respectively, by virtue of their equivalent distances relative to both needle drivers. Although limited by the power of our study (6 surgeons), the data indicate that bites taken at the 2- through 5-o'clock positions should be performed with a left forehand approach. A right forehand approach should be used for the 6- through 9-o'clock positions, and a left backhand technique optimizes results for the 10- and 12-o'clock positions. This information may be used for training surgeons in robotic surgery techniques.

Optimization of Target-Plane Angle

The data obtained from tilting the plane of the target vessel demonstrated the benefits of optimally setting up an anastomosis while operating in a robotic environment. The poor performance in the -45° group was due to the limited ability of the robotic instruments, which had to reach over the target plane, to maneuver and their tendency to collide with the target plane. The inferior results for the 135° plane could be attributed to unconventional visualization and the decreased dexterity of the robotic instruments at this angle. Unlike all other positions where one sews looking down, the surgeon must perform this anastomosis by sewing a vessel "on the ceiling." Future experiments in which the image is digitally flipped upside down and inverted left to right might demonstrate improved results. An endoscopic manipulator capable of rotating the vessel and altering the vessel's plane would significantly aid in performing this challenging anastomosis, especially for the 10-o'clock stitch, and could overcome some of the technical challenges involved in robotic multivessel CABG.

The data suggest that the optimal plane orientation is between the horizontal and +45°. Although the +45° position improves instrument dexterity because the robotic instrument shafts are orthogonal to the target plane, the camera view, which appears positioned directly above the ostomy, limits depth perception. Future experiments may be aimed at optimizing results by varying the camera angle while the plane is held at this inclination.

CONCLUSION

Although robotic devices have been available for several years, there has not been a widespread application to closed-

chest coronary surgery, which remains a technical challenge confined to a few pioneering clinicians. The reasons for the lack of progress in coronary surgery are likely multifactorial. We have sought to quantify human performance by using a current robotic device, with the aim of optimizing our use of the device and possibly aiding future engineering refinements.

The findings of this study suggest that when an anastomosis of a graft to a coronary artery is performed robotically, the speed and accuracy of the procedure can be improved by making small changes in vessel orientation. Vessels should be positioned between the horizontal and diagonal orientation and inclined between the horizontal and $+45^\circ$. Because the 6-o'clock stitch is particularly challenging, surgeons may benefit from an orientation that moves the heel or the toe of the anastomosis away from this critical position.

ACKNOWLEDGMENTS

The authors extend their gratitude to the cardiac surgeons, especially Drs. Joren Madsen, Jennifer Walker, and Yoshiya Toyoda, who graciously donated their time and shared their insights during the course of this study. We also thank Lisa Wendt of Edwards Lifesciences for furnishing us with samples

of PTFE tubing. We are grateful to the Center for Integration of Medicine and Innovative Technology (CIMIT) for generously supporting our research in robotic surgery.

REFERENCES

- Boyd WD, Rayman R, Desai ND, et al. 2000. Closed-chest coronary artery bypass grafting on the beating heart with the use of a computer-enhanced surgical robotic system. *J Thorac Cardiovasc Surg* 120:807-9.
- Duhaylongsod FG. 2000. Minimally invasive cardiac surgery defined. *Arch Surg* 135:296-301.
- Kappert U, Cichon R, Schneider J, et al. 2000. Closed-chest coronary artery surgery on the beating heart with the use of a robotic system. *J Thorac Cardiovasc Surg* 120:809-11.
- Reichenspurner H, Boehm D, Gulbins H, et al. 1999. Robotically assisted endoscopic coronary artery bypass procedures without cardiopulmonary bypass. *J Thorac Cardiovasc Surg* 118:960-1.
- Reichenspurner H, Damiano R, Mack M, et al. 1999. Use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. *J Thorac Cardiovasc Surg* 118:11-6.
- Talwalkar NG, Cooley DA. 1998. Minimally invasive coronary artery bypass grafting: a review. *Cardiol Rev* 6:345-9.