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Evaluation of Acute Traumatic Changes of the Coronary Artery Wall After Robotically Assisted Endoscopic Coronary Artery Bypass Grafting

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ABSTRACT

Background: There is concern that the technical limitations of robotic systems used in endoscopic coronary artery bypass grafting (CABG) may lead to increased trauma of the anastomotic site. To examine this issue, we compared the acute traumatic changes of the coronary artery wall caused by conventional manual suturing and robotically assisted suturing for anastomoses using the ZEUS™ telemanipulator (Computer Motion Inc., Goleta, CA) in a laboratory setting.

Methods: Coronary artery bypass grafting was performed on isolated porcine hearts. Fifteen anastomoses (with harvested porcine right coronary artery (RCA) segments) were carried out using the ZEUS™ microsurgical telemanipulator (group Z), while 15 further anastomoses were performed with a conventional manual technique (group M) using Gore-Tex CV-8 suture material. Specimens were taken from each anastomotic site and from native parts of the left anterior descending artery (LAD) (control group). Morphological changes of the cellular and fibrous components of the lamina intima and lamina media, and the shape and maximum diameter of the puncture mark, were examined by light microscopy (LM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). Vascular endothelial damage and denudation were graded on a score from 1 to 5.

Results: In each group, 14 specimens were evaluated. SEM findings showed a significantly higher degree of endothelial denudation in group Z and group M compared to the control group, while group Z was significantly more affected than group M. Likewise, the maximum diameter of the puncture mark was significantly larger in group Z than in group M. TEM and LM studies supported these results. In addition, LM revealed that in five specimens of group Z the shape of the stitch through the artery wall was not cylindrical, as in the other cases, but was asymmetrical and displayed a superficial furrow on the side of the vascular lumen.

Conclusion: The results indicate that there is an increased incidence of damage to the coronary artery wall caused by the microsurgical telemanipulator. Further studies are necessary to determine whether the differences between conventional and robotic-assisted suturing techniques will have an effect on the long-term outcome of coronary artery bypass grafting.

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INTRODUCTION

Microsurgical telemanipulators have recently been introduced into cardiac surgery to facilitate minimally invasive procedures such as endoscopic coronary artery bypass grafting (CABG). These systems enable surgeons to manipulate instruments very precisely, a technique, which led to closed-chest CABG even on the beating heart [Reichenspurner 1999a, Reichenspurner 1999b, Boyd 2000a, Kappert 2000]. However, the currently available systems still have major technical limitations. For the ZEUS™ telemanipulator, these limitations include the lack of tactile force feedback and the limited range defined by five degrees of freedom at the tip of the robotic instruments. Although the results of the clinical use of telemanipulators at our facility [Boehm 2000] were similar to conventional manual suturing techniques, there was concern that the limitations of the telemanipulator might have a negative effect on the quality of the anastomoses. To examine this question, we compared the acute traumatic changes of the coronary artery wall following conventional manual suturing with robotically assisted suturing in a laboratory setting.

MATERIALS AND METHODS

Fifteen porcine hearts were excised at the slaughterhouse. The orifices of the coronary arteries were gently flushed with Bretschneider's solution before the whole organ was immersed in a plastic bag filled with Bretschneider's solution and wrapped in another plastic bag. For transportation, the plastic bags were placed in a cool box filled with ice, identical to the method for transporting human donor hearts. The storage temperature was between 0° and 4° Celsius.

In the laboratory, two anastomoses with free segments of the right coronary artery (RCA) and the left anterior descending artery (LAD) were performed on each heart—one in conventional open manual technique (group M) and the other using the ZEUS™ Telemanipulator (Computer Motion Inc, Goleta, CA) (group Z). All suturing was performed by one surgeon who had undergone a thorough training program with the ZEUS™ system, including 40 anastomoses on pig hearts prior to the ones evaluated in this study. After the LAD was prepared and incised, stay sutures were placed in the epicardium (Prolene 7-0, Ethicon GmbH & Co. KG, Norderstedt, Germany). A free segment of the RCA was approximated to the LAD by a u-stitch at the proximal end of the incision before the anastomosis was performed in a running manner using custom-made 7 cm double-armed CV-8 Gore-Tex sutures (W. L. Gore & Associates GmbH, Putzbrunn, Germany). Manual suturing was done using conventional needle holders and forceps. The hearts were placed on a table to allow wide access similar to open chest surgery.

When the anastomoses were performed with the ZEUS™ telemanipulator, the porcine hearts were placed in a human thoracic model and oriented to reproduce the orientation of the *in vivo* human heart. The thoracic model consisted of a reproduction of the human rib cage covered with a layer of neoprene to simulate the soft tissues of the human thorax. Access for the instrument ports was created in the third and seventh intercostal spaces along the anterior axillary line, while the endoscopic camera was inserted through a port in the fifth intercostal space at the mid-subclavian line. For instrumentation, needle holders with curved tips were used, allowing a total of five degrees of freedom. Visual control was established with the Vista stereo-matchbox camera (Vista Medical Technologies Inc., Westborough, MA). The 3D image was displayed on two liquid crystal display (LCD) monitors inside a headset (Vista Medical Technologies Inc., Westborough, MA). The camera and the instruments were positioned by the robotic arms of the ZEUS™ telemanipulator, which were controlled remotely from the console. The setup was chosen to guarantee optimal working conditions for the ZEUS™ system.

After completion of the anastomoses, specimens were taken from the anastomotic site and fixated for light microscopy (LM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). Additional specimens were taken from native parts of the LAD, which served as a control group. The maximum storage time of the pig hearts between excision from the animals and the fixation after completion of the anastomosis was two hours.

The SEM specimens were fixated in glutaraldehyde, dried according to the critical point method (Bal-Tec Critical Point Dryer CPD 030, Balzers Union AG, Balzers, Liechtenstein) and coated with a thin layer of gold (Bal-Tec Sputter Coater SCD 050, Balzers Union AG, Balzers, Liechtenstein). The suture material remained in the specimens to facilitate the location of the puncture marks.

Using a Leica S420 scanning electron microscope (Leica Cambridge Ltd., Cambridge, UK), the maximum diameter of the stitches was measured (magnification 300x). In four fields of 80x80 micrometers, adjacent to the stitch per specimen, the denudation of the vascular endothelium (magnification 3000x) was graded on a score from 1 to 5 (1 = no endothelial denudation, 5 = completely denudated subendothelial structures). Results from the control group were compared with specimens where the stitches were performed manually (group M) or with the ZEUS™ system (group Z).

Other specimens were fixated in glutaraldehyde and osmium tetroxide, dehydrated, and embedded in araldite (Araldite CY 212, Serva, Heidelberg, Germany). Semi-thin sections along the path of the needle through the wall of the LAD were stained with toluidine blue and examined by LM. The shape of the stitch was evaluated (magnification 400x) and the degree of endothelial damage was graded on a score from 1 to 5 (1 = no endothelial damage, 5 = complete destruction of endothelial cells).

Ultrathin sections obtained from the embedded specimens were stained with uranyl acetate and lead citrate prior to examination in a TEM (Philips CM 10, Philips, Hamburg, Germany). In these cross-sections of the arterial wall, the degree of endothelial denudation adjacent to the stitch was graded on a score from 1 to 5 (1 = no endothelial denudation, 5 = completely denudated subendothelial structures) and morphological changes of the components of the different layers of the arterial wall were registered.

Computer-based statistical comparison of all groups (M, Z, and control) was performed with SPSS for Windows 9.0.1 using the Wilcoxon test (for endothelial damage and denudation), the Student's t-test (for maximum diameter of the puncture mark), and the Fisher's test (for shape of the puncture mark). A p-value of less than 0.05 was considered statistically significant.

RESULTS

In each group 14 specimens were evaluated. Specimens of the control group examined by SEM displayed a low degree of endothelial denudation of the intima. The luminal surface was almost continuously covered by a layer of endothelial cells that was only occasionally interrupted by cellular gaps or widened intercellular spaces. The morphology of the endothelial cells varied from the normal spindle-shaped cells to swollen cells or cells with crater-like defects in the cellular membrane. In the specimens obtained from anastomotic sites (groups Z and M), a much higher degree of endothelial denudation prevailed (Figure 1,). Large areas of subendothelial connective tissue were exposed or only covered by scattered endothelial cells. Statistical comparison of the three groups revealed that there was a significantly higher degree of endothelial denudation in groups Z and M than in the control group (p (0.001) and a significantly higher degree in group Z than in group M ($p = 0.019$). In group Z, the maximum diameter of the puncture mark (Figure 2,) on the intimal side of the arterial wall was significantly larger (mean: 209.99 (m, SD: 29.98) than in group M (mean: 156.07 (m, SD: 87.00) ($p = 0.045$).

The shape of the puncture mark was evaluated by LM on cross-sections of the arterial wall. In group M the defects caused by the suture material presented as symmetrical channels with parallel boundaries (Figure 3,). In contrast to these results, in five specimens of group Z the defects also displayed a furrow in the intimal layer on one side of the stitch (Figure 4,). This was found to be significantly accumulated in group Z ($p = 0.02$). Differences in endothelial damage between group M and group Z were not significant, but groups M and Z showed a significantly higher degree of endothelial damage than the control group (p (0.001).

TEM revealed almost complete destruction of the endothelial lining, particularly close to boundaries of the stitches in group M and Z. There was no statistical proof for a difference between groups M and Z, but again a significantly higher degree of endothelial denudation (Figure 5,) occurred in those groups than in the control group ($p = 0.004$ and p (0.001, respectively).

DISCUSSION

The results of this study suggest that, under certain conditions, application of a telemanipulator during suturing of anastomoses increases damage to the arterial wall. Even in the control group a low grade of endothelial damage was detectable. A variety of conditions to which the tissue was exposed during the experiment may account for the damage: ischemia, hypothermia and rewarming [Hidalgo 1995, Eberl 1999], storage in Bretschneider's solution [Solberg 1989], and preparational methods for microscopy [Gregorius 1975]. On the other hand, the much higher degree of endothelial damage adjacent to the stitch in groups M and Z is strongly related to the technique of suturing. The comparison of the paths of the needle through the arterial wall expressed in the shape of the remaining arterial wall damage implies that, in some specimens of robotically sutured anastomoses, the needle could not be positioned perpendicular to the luminal surface of the coronary artery. This lead**s** to a furrow-like destruction of superficial layers of the intima and media when the tip of the needle scratches over the luminal surface before it penetrates the entire wall, suggesting that greater lateral forces were exerted on the surrounding tissue than in the manually sutured anastomoses. Therefore, SEM revealed a significant difference in endothelial damage between manually and robotically assisted sutured anastomoses. TEM analysis revealed no difference because the fields that were examined were very close to the stitch and the endothelial layer in that area was completely destroyed. However, in the sections evaluated by LM, the portion of the endothelium that was influenced by the forces of the suturing process was very small, and no difference in the amount of damage was detected. Furthermore, the magnification for LM was too low to identify the morphological changes of individual endothelial cells. This is probably one reason why two other studies that compared the quality of manual and robotic-assisted constructed anastomoses by gross pathological examination revealed no differences between the two techniques [Falk 1999, Boyd 2000b].

Endothelial damage and exposure of highly thrombogenic subendothelial structures are a basis for thrombus formation and vasospasm, which are known to be factors for early graft failure. On the other hand, intimal hyperplasia is also initiated by endothelial damage [Ross 1986, Davies 1993]. Although it is not clear whether the higher degree of endothelial denudation found in group Z is extensive enough to influence the clinical results of endoscopic bypass grafting, it is possible that there is a higher risk for early and late graft failure.

The users of microsurgical telemanipulators should be aware of these potential limitations. The study was not designed to differentiate between the effects of the imaging system and the telemanipulator, although the quality of visualization and the gain in resolution might well have an influence. Highly sophisticated telemanipulator systems enable surgeons to manipulate very precisely, but this advantage is restricted to the optimal working conditions of the telemanipulator. Working close to the limits of the range of motion of robotic arms may lead to increased tissue damage, which in turn may have an adverse effect on the long-term outcome for these procedures. In order to minimize these adverse effects, thorough training and exact knowledge of the technical limitations of the telemanipulator are absolutely necessary.

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REFERENCES

1. Boehm DH, Reichenspurner H, Detter C, et al. Clinical use of a computer-enhanced surgical robotic system for endoscopic coronary artery bypass grafting on the beating heart. Thorac Cardiovasc Surg 48:198-202, 2000.
2. Boyd WD, Rayman R, Desai ND, et al. 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, 2000.
3. Boyd WD, Desai ND, Kiaii B, et al. A comparison of robot-assisted versus manually constructed endoscopic coronary anastomoses. Ann Thorac Surg 70:839-43, 2000.
4. Davies MG, Hagen PO. The vascular endothelium—a new horizon. Ann Surg 218:593-609, 1993.
5. Eberl T, Salvenmoser W, Rieger G, et al. Ultrastructural analysis of human endothelial cells after hypothermic storage in organ preservation solutions. J Surg Res 82:253-60, 1999.
6. Falk V, Gummert J, Walther T, et al. Quality of computer enhanced totally endoscopic bypass graft anastomosis—comparison to conventional technique. Eur J Cardiothorac Surg 15:260-6, 1999.
7. Gregorius FK, Rand RW. Scanning electron microscopic observations of common carotid artery endothelium in the rat: I. Crater artifacts. Surg Neurol 4:252-7, 1975.
8. Hidalgo MA, Sarthchandra P, Fryer PR, et al. Effects of hypothermic storage on the vascular endothelium: a scanning electron microscope study of morphological changes in human veins. J Cardiovasc Surg 36:525-32, 1995.

9. Kappert U, Cichon R, Schneider J, et al. Closed-chest coronary artery surgery on the beating heart with the use of a robotic system. J Thorac Cardiovasc Surg 120:809-11, 2000.
10. Reichenspurner H, Damiano R, Mack M, et al. Use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. J Thorac Cardiovasc Surg 118:11-6, 1999.
11. Reichenspurner H, Boehm DH, Gulbins H, et al. Robotically assisted endoscopic coronary artery bypass procedures without cardiopulmonary bypass. J Thorac Cardiovasc Surg 118(5):960-1, 1999.
12. Ross R. The pathogenesis of atherosclerosis—an update. N Eng J Med 314:488-500, 1986.
13. Solberg S, Larsen T, Lindal S, et al. The effects of two different crystalloid solutions on cultured human endothelial cells. J Cardiovasc Surg 30:669-74, 1989.