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Real-time three dimensional echo-guided closure of atrial septal defect: an experimental model

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Abstract

Real-time 3D echo may open the way to off-pump closure of an atrial septal defect with a robotic surgery technique without remnant of closure device. We report the preliminary results of 3D echo-guided closure of defect in an experimental model. A sheet with an oval defect immersed in water was visualized with 3D echo as well as surgical instruments. The defect was closed under echo guidance. Visualization of objects and instruments, and feasibility and problems of this technique were examined. The defect was visualized like an endoscopic view. Changing the view point without moving the transducer was a unique advantage. Visualization of instruments was acceptable with the lowest gain level. Acoustic shadow was helpful for comprehending the spatial relationship among the objects. Position of needle entry could be confirmed by the movement of the sheet. As the defect was sutured, fold convergence appeared on the sheet. Difficulties were encountered in passing the needle between instruments because of echo dropout. The string was poorly visualized. 3D echo-guided suturing was feasible with adequate image quality. However, an improvement of the surface of instruments and a wider scanning area is necessary for achieving surgical procedures with more safety and reliability.

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1. Introduction

Skin incision for surgical treatment of atrial septal defect (ASD) was previously too large. Efforts to minimize the incision were made in two ways: (1) surgical procedures with minimal incision such as right thoracotomy or minimally invasive cardiac surgery and (2) catheter closure of the defect. The former attempts have reached totally robotic surgery with endoscopic guidance [1,2]. However, cardiopulmonary bypass was essential for obtaining a bloodless field for visual assistance. In the latter attempts, a specially designed device is implanted to occlude the defect [3,4]. The device, however, remains in place and generates a risk of dislodgement or infection. It may interfere with future treatments in the long period of follow up, such as catheter ablation for atrial fibrillation. If suture closure of the defect is feasible without bloodless field, it would be most desirable.

Echocardiography has been utilized for guiding manipulation of catheters or instruments since it can visualize both catheters and cardiac structures without evacuating the blood. They include percutaneous transvenous mitral commissurotomy (PTMC) [5], placement of intraaortic balloon catheter [6], pulmonary arterial catheter [7], stent graft implantation for aortic aneurysm [8,9], or transcatheter closure of ASD [10,11]. The two-dimensional images of echo views, however, caused a limitation of echo-guided procedures because any objects out of the scanning plane cannot be seen.

Recently developed real-time three dimensional (3D) echocardiography has provided us with perspective views of cardiac structures as seen endoscopically and is anticipated to be applicable to guiding surgical procedures. To our best knowledge, there is only one report of real-time 3D echo-guided procedure [12]. However, technical aspects of echo-guided procedures were not described in detail.

The purpose of the current study is to clarify: (1) how clearly the instruments can be visualized; (2) whether 3D echo-guided suture is feasible and accurate; and (3) the problems to be solved for achieving safe and secure procedures, by using an in-vitro experimental model of ASD closure.

2. Materials and methods

A thin polyvinyl sheet with an oval defect of approximately 1 × 2 cm was fixed to an open box, simulating an atrial septum with defect. This model was immersed in water and was scanned with a real-time 3D echo system (SONOS 7500: Phillips Medical Co. Inc., USA). The echocardiographic probe was wrapped with a thin vinyl sac with some sonographic jelly on the transducer and was immersed in water for scanning the defect (Fig. 1). The sheet with defect was scanned obliquely with the transducer fixed at several
Fig. 1. Photograph demonstrating the experimental model. A sheet with oval defect is immersed in water and is visualized with real-time 3D echo, scanned obliquely.

Fig. 2. Echogram showing changed viewpoint by trackball. It is not necessary to move the transducer.

Fig. 3. Echogram showing opening and closing of forceps for grasping the needle. The needle holder is depicted on the right. Acoustic shadow from the forceps is shed on the septum.

Video 1. Video showing a needle piercing the septum and grasped by a needle holder.

3. Results

3.1. Echo view of defect and instruments

Fig. 2 and Video 1 shows the echo view before suturing. The defect portion was clearly depicted as an oval-shaped echo-free defect in the echogenic sheet. While the defect was scanned obliquely, the viewpoint could be freely adjusted with trackball: frontal view, oblique view, tangential view, or even the view from the left atrial side.

The surgical instruments were depicted as strongly echo-genic and generated artifacts such as acoustic shadow, reverberations, or side lobes as in 2D echo. In this setting, the following issues were examined:

1. visualization of the defect and instruments
2. panel setting suitable for visualization of these objects
3. feasibility of grasping the edge of defect and needle with forceps

Then the defect was sutured under echo guidance but without direct vision. In this procedure, the following were examined:

4. feasibility of suture ligature of defect without direct vision

5. technical and ultrasonographic problems of this procedure to be solved

Fig. 3. Echogram showing opening and closing of forceps for grasping the needle. The needle holder is depicted on the right. Acoustic shadow from the forceps is shed on the septum.
became unclear when the portion of forceps was nearly parallel to the ultrasonic beam. Visualization immediately improved by rotating or tilting the tip of the forceps or by changing the position of the transducer.

The needle holder appeared quite differently from the endoscopic (optical) view (Figs. 3, 4, Videos 1, 2). Only a limited portion perpendicular to the ultrasound beam was visualized. It also caused wide acoustic shadow shed on the septum. A needle was depicted as an echogenic arc with minimal acoustic shadow behind it. Although it was readily identified, the needle tip was hardly visible unless this portion was situated perpendicular to the ultrasound. As the needle tip was grinded finely to make the surface rough, it became more clearly visualized. It was difficult to visualize the entire portion of polypropylene suture. Although the portion that is perpendicular to the ultrasound beam was depicted as echogenic, the largest portion of suture was not identified because of its smooth surface. It caused little acoustic shadow because of its small diameter compared with the resolution of ultrasound (0.5 mm). The braided suture of the same diameter was more clearly visualized because it caused diffuse reflection.

In the current system there are six modes of display for 3D images with different settings (A to F). The transparency mode generated minimal artifact and the side lobes were less annoying, while the surface rendering mode caused considerable artifacts and appeared unsuitable for guiding the procedures. Transparency mode (mode E) was not appropriate for identifying the spatial relationship between the instruments. The non-transparent mode with minimal gain level and wide dynamic range was most suitable for visualization (mode F).

3.2. Grasping and suturing

The spatial relationship between the forceps and sheet was readily identified; the forceps behind the sheet was hidden by the sheet. The margin of defect could be easily grasped by the forceps or touched by the needle tip. It was apparent because the sheet moved when it was touched or grasped. Pressure or traction of the sheet was also readily identified by the distortion of sheet.

When the needle pierced the sheet, the point was seen slightly depressed. The needle could be pierced at an appropriate position by sliding the needle tip from the margin of the defect. The needle behind the septum was hidden by the septum and the needle tip appeared in the defect (Fig. 4, Video 1). The needle piercing the opposite side of septum caused protrusion of septum by the needle tip. Accuracy of piercing position was confirmed by inspection after suture (Fig. 5).

After tying the string, a fold convergence toward the knot appeared on the sheet (Fig. 6, Video 2). This finding clearly showed the location of knot and was helpful for determining the next suture point despite the string itself being hardly visible. As the defect was continuously sutured, a traction of string caused convergence of edges and clarified the position of previous suture.

3.3. Problems encountered in this model

When the defect was continuously sutured, the string was occasionally interlocked because the needle passed through a loop of string. This occurred when the string was not strained appropriately.

After fold convergence appeared, a portion of sheet appeared like a defect because this portion became nearly

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**Fig. 4.** Echogram showing a needle piercing the septum. The needle tip is seen in the defect and the portion behind the septum is hidden.

**Fig. 5.** Photograph showing the result of suture under real-time 3D echo guidance. The position of suturing is appropriate.

**Video 2.** Video showing the suturing procedures of defect and formation of fold convergence after the thread is tied.
parallel to the ultrasound beam. This problem could be solved by moving the position of the echocardiographic probe.

It was often difficult to pass the needle from the needle holder to the forceps because the tip of the needle was hardly visible. Position of the needle tip was identified by touching the needle with the forceps.

The range of 3D echo image was narrow and the object often escaped out of the view. An adequate distance from the transducer to the object was helpful for keeping a wider field of vision.

4. Discussion

Real-time 3D echo provides perspective views like endoscopic views and enables us to manipulate the surgical instruments and suture the defect without watching in direct vision in the current experimental motionless model. Visualization of instruments and objects is mostly acceptable after the panel settings are appropriately adjusted. The artifacts specific to the echo views are not problematic. Acoustic shadow is rather helpful for comprehending the spatial relationship of each instrument.

Under real-time 3D echo guidance, the view point can be freely changed without moving the transducer and the bloodless field is not needed for surgical procedures. These are unique advantages of echo-guided surgery, which cannot be achieved by endoscopic guidance.

However, accuracy and easiness of surgical procedures under echo guidance is far from satisfactory, when compared to the endoscopic guidance. The most serious problem is echo dropout, which makes it difficult to pass the needle between the instruments and to view the whole portion of suture. It seems to be caused by the following reasons: (1) smooth surface of instruments which reflects ultrasound elsewhere; (2) low resolution of images due to low frequency of ultrasound (3.5 MHz); and (3) a narrow view field (30 degrees).

The surface of instruments needs to be modified so as to reflect the ultrasound diffusely and to be better depicted. Braided suture was visualized much more clearly than polypropylene suture. Renovation of echo system will solve the latter two problems: higher frequency of ultrasound (5–7 MHz) and wider scanning field (60–90 degrees).

Suematsu et al. [12] reported that the frame rate was a problem to be solved. For guiding the surgical procedures in the beating heart, the frame rate should be high enough. In the current system, the frame rate has been increased to higher than 20 Hz.

The current system displays the 3D view as a 2D image. Stereovision developed for an endoscopic surgery or robotic surgery would greatly facilitate the echo-guided surgery as well by using specially prepared glasses or display system.

In this study, the ASD model and instruments were immersed in water, not in blood, because blood causes spontaneous echo contrast in such a static model and cannot simulate the views obtained in the beating heart model. The instruments were visualized with echo dropout as expected from the experiences of visualizing catheters and other foreign bodies in the heart and vessels in the clinical setting [13].

The next step needed would be a study in an animal model or an in-vitro model with pulsatile blood flow. Real-time 3D echo-guided surgery may be applied not only to closure of ASD but to tricuspid annuloplasty, mitral valve repair such as edge-to-edge mitral valve procedures, and so on. Further development is mandatory toward the clinical application, ultimately to the complete robotic surgery under 3D echo guidance.

References

Appendix. Conference discussion

_**Discussant** (not known):_ I have torrents of questions, but let me restrict it to one question.

You aim at off-pump surgery. So you need to go into the right atrium with your instruments without spilling too much blood. So do you have already an idea how to do so?

**Dr Orihashi:** There must be several steps. We can’t go to the last goal at one step. Now, first, we have to go to just thoracotomy and off-pump procedures using some port, like endoscopic surgery.

Next we can go to the robotic surgery with small incision or from the jugular vein and femoral vein. Such special instruments should be developed. But before that, we can’t put the transducer on the heart.

**Dr H. Vanermen (Aalst, Belgium):** I want to make one additional comment. I think it may be very, very interesting though in the future for the surgical community, because it will allow us, just like you told us. If one day we have real-time 3-D probes in the esophagus, it will allow us, for example, to position the valved stent in the aortic position way better than we can do even with fluoroscopy, and in the mitral position as well maybe eventually. So I think it’s extremely interesting.