A novel device for left atrial appendage exclusion: The third-generation atrial exclusion device

Hideyuki Fumoto, MD,[a] A. Marc Gillinov, MD,[b] Yoshio Ootaki, MD, PhD,[a] Masatoshi Akiyama, MD, PhD,[a] Diyar Saeed, MD,[a] Tetsuya Horai, MD,[a] Chiyo Ootaki, MD,[a] D. Geoffrey Vince, PhD,[a] Zoran B. Popović, MD,[c] Raymond Dessoffy, AA,[a] Alex Massiello, MEBME,[a] Jacquelyn Catanese, MA,[a] and Kiyotaka Fukamachi, MD, PhD[a]

Objective: Occlusion of the left atrial appendage is proposed to reduce the risk of stroke in patients with atrial fibrillation. The third-generation atrial exclusion device, modified to provide uniform distribution of pressure at appendage exclusion, was assessed for safety and effectiveness in a canine model and compared with a surgical stapler.

Methods: The atrial exclusion device consists of 2 parallel, straight, rigid titanium tubes and 2 nitinol springs with a knit-braided polyester fabric. Fourteen mongrel dogs were implanted with the device at the base of the left atrial appendage via a median sternotomy. In each dog, the right atrial appendage was stapled with a commercial apparatus for comparison. The animals were evaluated at 7 days (n = 3), 30 days (n = 5), and 90 days (n = 6) after implantation by epicardial echocardiography, left atrial and coronary angiography, gross pathology, and histology.

Results: Left atrial appendage exclusion was complete and achieved without hemodynamic instability, and coronary angiography revealed that the left circumflex artery was patent in all cases. A new endothelial tissue layer developed on the occluded orifice of the left atrium 90 days after implantation. This endothelial layer was not evident on the stapled right atrial appendage.

Conclusion: In dogs, the third-generation atrial exclusion device achieved easy, reliable, and safe exclusion of the left atrial appendage with favorable histologic results. Clinical application could provide a new therapeutic option for reducing the risk of stroke in patients with atrial fibrillation.

The left atrial appendage (LAA) is a source of thrombus formation and may contribute to stroke in patients with atrial fibrillation (AF). The presence of AF increases the risk of stroke by 5-fold, and this risk increases with increasing patient age.[1] Anticoagulation therapy with warfarin is one of the most common therapies to prevent strokes, although anticoagulation therapy increases the risks of major bleeding (2.3% per year) and intracranial hemorrhage (0.9% per year).[2] Therefore, LAA exclusion has been increasingly discussed as a possible alternative for stroke prevention. Several investigators have reported novel techniques for LAA occlusion through thoracoscopic or percutaneous approaches.[3-7]

We previously reported preclinical investigations of a novel device, the atrial exclusion device (AED), which was developed for epicardial LAA exclusion on a beating or arrested heart.[8-10] The first-generation AED has 2 flattened bars made of stainless steel and covered with braided polyester knit fabrics.[9] One of the bars is flexible, and the other is rigid. During studies of this first AED design, the validity of the AED concept was confirmed. The second-generation AED, composed of 2 curved parallel and rigid titanium tubes and 2 nitinol springs with knitted-braided polyester fabric, incorporated modifications to prevent damage to surrounding tissues.[8] In the second-generation AED series, reliable and safe exclusion of the LAA was demonstrated. Subsequently, the shape of the second-generation AED was modified to improve the quality of LAA occlusion, and the present series, the third-generation AED,

ET

Abbreviations and Acronyms
AED = atrial exclusion device
AF = atrial fibrillation
ANP = atrial natriuretic peptide
BNP = brain natriuretic peptide
EE = epicardial echocardiography
LAA = left atrial appendage
LCX = left circumflex artery
RAA = right atrial appendage
2D = 2-dimensional

was designed. The purpose of this study was to evaluate the third-generation AED by epicardial echocardiography (EE), left atrial and coronary angiography, gross pathology, and histology. During evaluation of the third-generation AED, the right atrial appendage (RAA) was also excluded with a commercial linear stapling device for comparison with LAA exclusion achieved via the third-generation AED.

Materials and Methods
Design of the Third-generation Atrial Exclusion Device
The skeleton of the third-generation AED is composed of 2 parallel, straight, rigid titanium tubes with elastic nitinol springs arranged at a 90-degree angle at both ends of the tubes (Figure 1). To ensure that each segment between the opposing tubes has an equal distribution of force between them when the AED clips the LAA, the second-generation AED's curved titanium tubes have been redesigned into the straight tubes of the third-generation AED to allow for complete LAA occlusion. The third-generation AED used in this study was 35 mm in length. The rigid titanium tubes are covered with a urethane elastomer, and the entire skeleton is covered with a knit-braided polyester sheath, which promotes rapid ingrowth of fibrous tissue (Figure 1). The same delivery tool is used to apply to the LAA as in the previous study.[8] The AED can also be easily redeployed if it is placed at a suboptimal site.

Study Design
A total of 14 mongrel dogs, with a mean weight of 30.9 ± 2.8 kg, were used in the present study. The study was approved by the Cleveland Clinic's Institutional Animal Care and Use Committee, and all animals received humane care in compliance with the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources, National Research Council, and published by the National Academy Press, revised 1996.

Atrial Exclusion Device Implantation and Stapling
The dogs were placed under general anesthesia in the supine position. The pericardium was opened to expose the LAA and the RAA via a median sternotomy. A single Millar catheter (SPC350, Millar Instruments, Houston, Tex) was inserted in the left pulmonary vein to monitor the left atrial pressure, and a 14-gauge angiocatheter was placed into the pulmonary vein for left atrial angiography. The AED was delivered over the LAA and placed at the
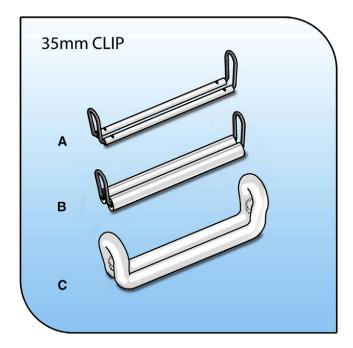

Figure 1. Skeleton of the AED. A, Two parallel, straight, rigid titanium tubes with elastic nitinol springs and a 90-degree angle at both ends of the tubes. B, The 2 straight tubes are covered with urethane elastomer. C, The whole skeleton is covered with a knit-braided polyester sheath. *AED*, Atrial exclusion device (third generation).

base of the LAA using the same delivery tool that had been used in the previous studies.[8] After the LAA was clamped, the RAA was stapled with a commercial apparatus (AutoSuture DST Series TA30; United States Surgical, Norwalk, Conn) to obtain a histologic comparison with the LAA occlusion via the AED.

Hemodynamic parameters consisting of arterial pressure, left atrial pressure, and heart rate were collected before (pre-LAA occlusion) and after implantation (post-LAA occlusion). Ventilatory support was transiently halted while data were acquired. Hemodynamic parameters were digitized in real time at a sampling rate of 200 Hz with a data-acquisition system (PowerLab, ADInstruments, Inc, Mountain View, Calif) and stored on a hard disk for subsequent analyses by a custom-made visual basic program on Excel software (Excel 2000, Microsoft Corp, Redmond, Wash). Two-dimensional (2D) EE and Doppler echocardiography were performed on the open chest before and after implantation. The left atrial volume was also assessed through a biplane area-length method from the apical 4- and 2-chamber views. The left ventricular end-diastolic volume (EDV) and end-systolic volume (ESV) were measured by single-plane Simpson's rule. Left ventricular ejection fraction was calculated by the equation $100 \times (EDV - ESV)/EDV$. The left ventricular stroke volume was calculated as the difference of EDV minus ESV. Data acquisition was performed as described in our previous report.[8] Left atrial and left circumflex artery (LCX) angiographies were performed in the 60-degree left anterior oblique and 30-degree right anterior oblique planes both before and after AED application.

ET

The chest was closed with a chest tube in place after confirmation of hemostasis. The dogs were carefully monitored for 7 days (n = 3), 30 days (n = 5), or 90 days (n = 6) in regular housing. Postoperative analgesics and antibiotics were administered; however, no anticoagulants or antiplatelet drugs were given during the postoperative period as a postoperative management.

Terminal Study

At study termination, the dogs were placed in the supine position under general anesthesia. The chest was reopened to expose the implanted AED through a median sternotomy. Hemodynamic assessment, left atrial angiography, 2D EE, and Doppler echocardiography were performed in the same manner as during the implant surgery. After these procedures, the dogs were sacrificed under full heparinization (500 U/kg) by rapid intravenous injection of sodium pentobarbital (50 mg/kg) and potassium chloride (120 mEq).

Gross Necropsy and Histologic Evaluation

The totality of LAA exclusion and the response of the tissue surrounding the AED were examined macroscopically. After the hearts were harvested, the AED with the LAA and the surrounding left atrium and left ventricular tissue were excised from the heart. Both nitinol springs at the edge of the AED were cut off, and the 2 straight tubes with exterior urethane were pulled out of the fabric covers that had adhered to the base of the LAA. A middle portion of the entire LAA, perpendicular to the AED, with the polyester fabric was taken for cross-sectioning. The cross-sectioned tissue samples were fixed in 10% formalin for 48 hours and embedded in paraffin. Sections were cut from each block at 4 μm and collected onto glass slides. All sections were then dried for 60 minutes at 60°C and stained with hematoxylin-eosin. The connective tissue underneath the AED and the LAA were assessed in cross-sections of the specimens. The stapled RAA was also assessed in the same way as the LAA. The stapled RAA was sliced perpendicularly to the staple for cross-sectioning in a similar fashion.

Atrial Natriuretic Peptide and Brain Natriuretic Peptide

The mean levels of atrial natriuretic peptide (ANP) and brain natriuretic peptide (BNP) were measured at the time of the implantation and reassessed at 14 days or 30 days after implantation in 6 cases (5 cases in the 30-day study and 1 case in the 90-day study).

Data Analysis

All values are expressed as mean ± standard deviation. Repeated-measures analysis of variance trials were used to assess the differences among pre-LAA exclusion, post-LAA exclusion, and terminal study.

Results
Procedure for the Atrial Exclusion Device Implantation

The AED was delivered easily on a beating heart in all dogs (n = 14) in approximately 10 seconds without major complications or hemodynamic instability. In all cases, 2D EE, Doppler echocardiography, and left atrial angiography revealed no communication between the LAA and left atrium and no blood flow in the LAA after implantation. Angiogra-

phy of the left coronary artery showed patent LCX in all cases. In 1 case of the 7-day study, the edge of the LAA was torn when it was held with forceps to deploy the AED. However, the LAA had been occluded with the AED, and no additional suture was needed for the injured site because the AED provided adequate compression forces to achieve acute exclusion. All animals survived the implant study without device-related complications, and their postoperative courses were uneventful.

Procedure for Stapling the Right Atrial Appendage

The RAA was stapled with the commercial apparatus. All stapling was accomplished with ease. However, a small quantity of blood oozed from the stapling in 3 of 4 early cases. All cases with oozing eventually acquired hemostasis without additional stitching, although the cases with oozing required a few moments until complete hemostasis was obtained with the assistance of manual compressing during the first few experiments. In the latter cases of this series, we used fabric sheets (Seamguard-Bioabsorbable: Gore and Associates Inc, Flagstaff, Ariz) to stanch bleeding from the stapled RAA. The 2D EE apparently showed no communication between the RAA and right atrium in all cases.

Hemodynamic, Echocardiographic, and Angiographic Data

Hemodynamic and echocardiographic data are shown in Table 1. There were no statistical differences among the studies in reference to hemodynamics. There were no significant differences in the 2D EE parameters, such as end-systolic left atrial volume, EDV, ESV, stroke volume, and ejection fraction. Doppler echocardiography and left atrial angiography revealed no communication between the LAA and the left atrial body and no blood flow in the LAA before the terminal study. Left coronary angiography showed neither stenosis nor obstruction after implantation (Figure 2).

Findings of the Left Atrial Appendage at the Terminal Study

The AED remained at the base of the LAA without migration in all cases. The AED did not affect adjacent structures, such as the left atrial body, LCX, great cardiac vein, or pulmonary artery. The AED demonstrated more pronounced adherence to the surrounding tissues, especially the pericardium, in the 90-day models than in the 30-day models. The AED did not adhere to the wall of the main pulmonary artery in any studies, but only to the fat surrounding the main pulmonary artery. Likewise, the AED did not interfere with the blood flow of the LCX or the great cardiac vein.

Examination of the Left Atrial Appendage at Necropsy

All of the AEDs from the 30- and 90-day studies were completely covered with translucent fibrous tissue (Figure 3, A),

ET

TABLE 1. Hemodynamics and echocardiographic data

	Pre-LAA exclusion	Post-LAA exclusion	Terminal study	P value
Hemodynamics				
Heart rate (beats/min)	109 ± 12	110 ± 13	118 ± 17	.076
SBP (mm Hg)	115 ± 13	111 ± 10	105 ± 16	.129
DBP (mm Hg)	72 ± 13	68 ± 14	65 ± 18	.429
Mean LAP (mm Hg)	9.8 ± 4.3	10.6 ± 4.4	8.4 ± 3.2	.129
2D EE				
End-systolic LAV (mL)[b]	17.9 ± 4.8	13.9 ± 2.8	17.3 ± 5.3	.096
EDV (mL)[a]	63.6 ± 17.9	59.4 ± 16.4	55.5 ± 12.4	.060
ESV (mL)[a]	36.4 ± 15.0	35.1 ± 14.7	32.1 ± 12.0	.142
SV (mL)[a]	27.1 ± 5.2	24.3 ± 4.8	23.5 ± 2.9	.160
EF (%)[a]	44.3 ± 8.7	42.6 ± 10.1	43.8 ± 9.3	.342

LAA, Left atrial appendage; *SBP,* systolic blood pressure; *DBP,* diastolic blood pressure; *LAP,* left atrial pressure; *2D EE,* 2-dimensional epicardial echocardiography; *LAV,* left atrial volume; *EDV,* end-diastolic volume; *ESV,* end-systolic volume; *SV,* stroke volume; *EF,* ejection fraction.
No significant difference was found among each data point. [a]These measurements were obtained from available data in 9 animals. [b]These measurements were obtained from available data in 7 animals.

although the AED had not yet been covered with tissue in the 7-day study. The internal surface of the occluded orifice to the LAA was straight and smooth in all of the studies (Figure 3, *B*). The orifice was covered with a white tissue. There was neither laceration nor hemorrhage along the occlusion line in any studies. No thrombus formation in the left atrium was found in any studies. In the 30-day study, a fibrous tissue had grown at the orifice to the LAA underneath the titanium tubes. In the 90-day study, the fibrous tissue had grown so firmly that the occluded appendage could not be detached when either of the AED tubes was removed. Also, the fibrous tissue could not be detached, even though it was pulled in the opposite direction by hand. In AEDs from the 7-day study, the fibrous tissue growth was still fragile. In regard to the occluded LAA, in the 90-day study the LAA had been completely organized and occupied by a well-organized thrombus or dense fibrous tissue (Figure 3, *A* and *C*). In the 30-day study, the LAA had been atrophied and had organized. The 7-day study demonstrated many thrombi in the still bulged LAA, although the LAA was completely occluded. In all studies (with the exception of that in which the LAA had been injured during AED implantation), the LAA showed no perforation.

Histologic Examinations of the Left Atrial Appendage

In all studies, the polyester fabric of the AED was infiltrated by fibroblasts that produced fibrous collagen, which implied a mild inflammatory reaction (Figure 4, *A*). In the 90-day study, a thick layer of fibrous tissue underneath the AED was found and the fibrous tissue was smoothly covered with a new endothelial layer (Figure 4, *B*). Although the 30-day study demonstrated fibrous tissue and a new endothelial layer, the fibrous connective tissue was less dense than that found in sections from the 90-day study. In regard to
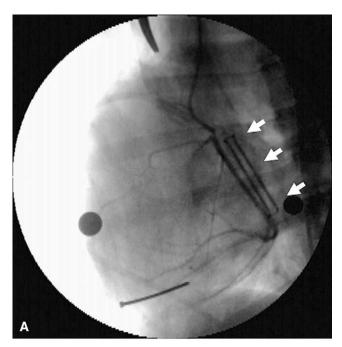
the wall of LAA occluded by the AED, myocardial tissue of the atrophied LAA was replaced by fibrous tissue in each 90-day study, whereas the LAA was replaced by fibrous tissue in only three of five 30-day cases, whereas the rest of the LAA had atrophied moderately. With regard to the 7-day study, the myocardium of the LAA had been infiltrated with fibroblasts.

Findings of the Right Atrial Appendage at the Terminal Study

EE revealed that the stapled RAA had no flow signal in all cases. The site at which the RAA had been stapled showed neither a remarkable reaction nor any abnormal adhesion to surrounding tissues. In half of the 90-day cases, bulging in the RAA was noted (Figure 5, *A*). In five of six 30-day cases, the RAA did not shrink, and there was some residual muscle tissue. In the 7-day study, the RAA remained as it had been at the implantation.

Examinations of the Right Atrial Appendage at Necropsy

The staple did not have any abnormal adhesion or affect surrounding organs, including the right ventricle or the right coronary artery in all cases. The internal surface of the stapled site also was found to be irregular because of the stapling (Figure 5, *B*). A part of the stapled RAA wall became thin, and the staple itself was seen from the right atrium (RA). A new fibrous tissue observed in the LAA was not apparently found on the stapled RA wall even in the 90-day study. Some cases had small marks from intramural hemorrhages present along the stapled line. No thrombus was found in the right atrium, including on the stapled orifice to the RAA. There were no lacerations along the stapled line in any studies. The RAA cavity was totally occluded in all
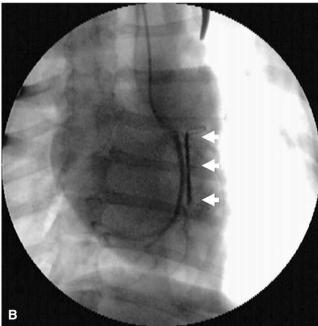
ET

Figure 2. Coronary angiogram of the LCX at the terminal study. No adverse effects of the implanted AED (*white arrows*) on the LCX were found in left anterior oblique 60-degree planes (A) or right anterior oblique 30-degree planes (B). *LCX,* Left circumflex artery; *AED,* atrial exclusion device (third generation).

cases. Three cases from the 90-day study (Figure 5, *C*), 4 cases from the 30-day study, and all 3 cases from the 7-day study showed that the RAA cavity was not yet organized and had bulged with noncoagulated blood. The other cases had organized clot in the RAA.

Histologic Examinations of the Right Atrial Appendage

The stapled sites did not yield a smooth fibrous tissue layer in any cases. A fibrous tissue at the stapled site had calcium deposition, which implies a severe inflammatory reaction (Figure 6, *A* and *B*). The endothelial surface also showed irregularities, and the endothelial surface did not resemble any of the new layers found on the LAA in appearance. All of the RAAs had not replaced the cardiac muscle with the fibrous tissue completely even in 90-day cases. The cases of the RAA that had not collapsed yet at the terminal study showed no evidence that the RAA wall had been replaced with fibrous tissue.

Atrial Natriuretic Peptide and Brain Natriuretic Peptide

The mean levels of ANP at preimplantation and 14 and 30 days postimplantation were 32.0 ± 20.4 pg/mL, 33.8 ± 13.6 pg/mL, and 41.2 ± 33.9 pg/mL, respectively. No significant differences were found among the data points. The level of BNP at every point was less than 5 pg/dL in all cases.
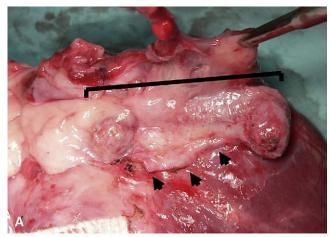
Discussion

The third-generation AED successfully isolated the LAA from the systemic circulatory system without any damage to adjacent organs in all cases. The procedure to implant the AED took approximately 10 seconds and did not affect hemodynamic parameters, including EDV, ESV, stroke volume, and ejection fraction. Fibrous tissue on the internal surface of the occluded closure line without any severe inflammation grew in response to the AED being implanted. The new endothelial layer of the left atrial orifice occlusion, created by the AED, was unique to only the LAA and not the RAA, which had been stapled. AED application did not create an interface between circulating blood and prosthetic material.

AF is the most common cardiac arrhythmia. The population of patients with AF who are aged more than 40 years has increased, and the population of patients with AF aged more than 65 years is increasing exponentially.[1,11] Currently, anticoagulation therapy reduces the risk of cardioembolic stroke in patients with AF. Such anticoagulation therapy offers many benefits, but there is also an increased risk associated with management of warfarin dosages within desirable ranges, as appropriate per age category.

A potential alternative therapy for stroke prevention in patients with AF is surgical exclusion of the LAA from the circulatory system.[5,7] Because thrombi commonly originate in the LAA of patients with AF, surgical LAA occlusion theoretically decreases the rate of strokes. However, according to the American College of Cardiology and American Heart Association guidelines, LAA occlusion is recommended only during mitral valve surgery.[12] Several techniques, including excision, ligation, suturing, or stapling for LAA exclusion, have been performed during concomitant cardiac
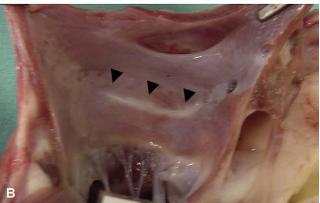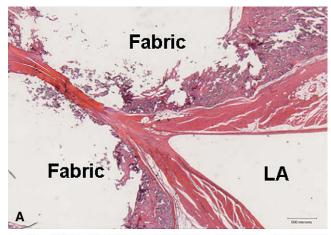
ET

Figure 3. Representative macroscopic images of the LAA in 90-day study. A, External surface of the left atrium. AED (*black bar*). The whole AED is covered with fibrous tissue. The LAA is completely atrophied (*black arrows*). B, Internal surface of the left atrium. The orifice of the LAA (*black arrows*) is completely occluded. The occlusion line is clear and smooth. Most of the occlusion line is filled with a white fibrous tissue. C, Cross-section of the LAA occluded by the AED. The thrombus in the LAA had already been organized. The polyester fabric is covered with thin, clear, whitish tissue, and the LAA wall is smooth. Thick fibrous tissue is seen beneath the AED (*white arrow*). LCX (*black arrow*). *LA*, Left atrium; *AED*, atrial exclusion device (third generation); *LAA*, left atrial appendage.
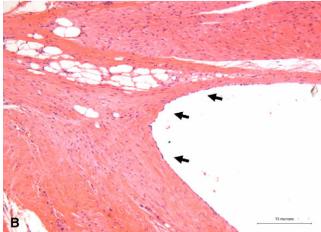
Figure 4. Representative microscopic images of the LAA in 90-day study. A, Thick fibrous tissue is shown underneath the AED (magnification ×16). B, The fibrous tissue is smoothly covered with a new endothelial layer (*black arrows*) (magnification ×100). *AED,* Atrial exclusion device (third generation); *LA,* left atrium.

surgery, because these relevant procedures can be easily accomplished. On the other hand, some reports have revealed that incomplete exclusion of the LAA after surgery actually can increase the risk of stroke rather than prevent stroke.[11,13]
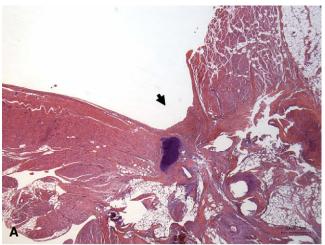
Although it seems easy to occlude the LAA with mere suturing, this standard surgical technique has been associated with bleeding and incomplete exclusion. Also, as Su and colleagues[14] have reported, the orifice of the LAA is not circular, but rather oval. This suggests that the best way to close the LAA might be along the longitudinal diameter. If the direction of LAA closure does not coincide with the longitudinal diameter, or if sutures are distributed unevenly, there may be increased risk of tissue tearing when the left atrium fills with blood. As in suture closure or excision, stapled closure or excision can cause tearing and bleeding of the LAA. In this study, stapling was associated with minor bleeding and delayed endothelial healing in comparison with AED implantation.
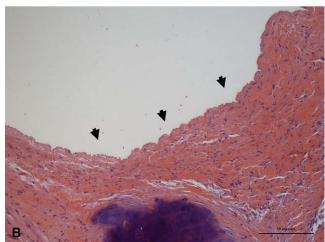
ET

Figure 6. Representative microscopic images of the RAA in the 90-day study. A, The stapled site (**black arrow**). Fibrous tissue was found at the stapled site with calcium deposition, which implies a pathologic reaction to what had been a locus of severe inflammation (a purple spot on the stapled site) (magnification ×16). **B,** The internal surface of the stapled site (**black arrows**). A new smooth endothelial layer that can be seen at the LAA occluded by the AED has not been created (magnification ×100). **LAA,** Left atrial appendage; **AED,** atrial exclusion device (third generation).

Figure 5. Representative macroscopic images of the RAA in 90-day study. A, External surface of the stapled right atrium. The RAA had not collapsed yet. Black arrows indicate the stapled line. **B,** Internal surface of the right atrium. The stapled orifice of the RAA (**black arrows**) has indentation, although the orifice is completely occluded. **C,** Cross-section of the occlusion site by the stapler. The RAA was not completely atrophied, but it had not been replaced with fibrous tissue yet. The thrombus in the RAA had not been organized yet. **RAA,** right atrial appendage.

Our previous studies during the transitional stages of AED development proposed the possibility of 2 issues. First, the force at each point on the curved tubes may not be distributed evenly when the AED with curved tubes opens widely in the case of a particularly thick LAA, although we have not experienced any incomplete closure because of LAA thickness. Second, the curved tubes of the second-generation AED were designed so that the curved shape was supposed to fit the shape of the LAA base. In previous studies, however, the shape of the curved tubes made a small pit proximal to the LAA occluded by the AED. No pits on the closed orifice that were seen in the previous study were seen in the present

study. As a benefit of the straight tubes, the LAA was closed more proximally to the left atrium than with the previously curved AED. Donnino and colleagues[15] have reported that thrombus formation was found at the proximal portion of the excluded LAA, although the distal LAA had been excluded successfully, possibly because the LAA was not excluded at the base of the LAA and the proximal portion was still in contact with the circulation. This highlights the importance of more proximal LAA exclusion. In addition, firm fibrous tissue grew underneath the AED. The occlusion was covered with a new endothelial layer in the 30- and 90-day studies. The new endothelial layer of the occluded orifice to the left atrium was found in both the present and previous studies. In addition, the AED will be adapted for less-invasive cardiac surgery in the future. The AED could be applied on a beating heart via a small thoracoscopic incision or via the subxyphoid approach if a delivery tool is developed for minimally invasive surgery.

We compared RAA stapling with the AED. The stapling caused bleeding from the targeted site.[16,17] Also in the present study, all cases except for those including fabric sheets to reinforce the stapled sites required a few moments of compression to stop bleeding, although no case needed to be sutured additionally to stop bleeding. However, the RAA was totally occluded by stapling. The perforation of the wall by staples caused severe inflammation, which was shown histologically in the present study. The internal surface provided by the stapling is indented, and the force to occlude the orifice is not distributed evenly. The AED promoted organization of the atrial wall and occluded appendage more rapidly, which could be associated with evenly adequate distribution of the pressure by the AED on the occluded closure line. In addition, a new fibrous tissue observed in the LAA was not apparently found on the stapled RA wall even in the 90-day study. The diameter of the AED tubes is approximately 5 mm, which is larger than the diameter of the staple. The large diameter of the AED provides greater contact area of opposing atrial walls and shorter distances between opposing atrial walls in the atrium proximal to the AED, which enables the development of fibrous tissue. The fibrous tissue was not observed at the proximal site of the stapled RAA. The fibrous tissue in the LA was too thick to be detached by hand. Therefore, the AED is thought to be superior to stapling. However, we excluded the LAA by the AED and the RAA by the stapler. It is a limitation of this study that there are fundamental differences in left and right atrial tissue properties, anatomy, and physiology. One limitation of the present study is that there is no one-to-one comparison between stapling of the LAA versus LAA occlusion by the AED.

The LAA is a potentially important structure, functioning as an endocrine organ that releases ANP and BNP.[18,19] ANP is secreted by the atrium in response to atrial stretch, and the ANP concentration is 40-fold higher in the LAA than in other parts of the atrial wall or in the ventricles.[18] Several investigators have demonstrated that the level of plasma ANP decreased after bilateral atrial appendectomy in animal models. In clinical settings, attenuation of ANP has been found in patients after the maze procedure and bilateral atrial appendectomy.[20,21] This implies that amputation of both atrial appendages could affect renal function. In the present study, however, there was no significant attenuation of ANP before or after bilateral atrial appendage occlusion. No clinical signs of heart failure, including general fatigue or significant changes in the animals' weight, occurred. There are 2 reasons why ANP levels did not diminish in the present study. First, neither the LAA nor the RAA was resected, which means that appendages were merely closed. Although 3 of the LAAs clipped by the AED were completely organized and replaced by fibrous tissue, the rest of the LAAs and all RAAs were not completely organized yet. In addition, we did not evaluate the levels of ANP under the condition of loaded blood volume. If we had loaded the volume to the animals, we would have found the influence from bilateral atrial appendage exclusion. However, one limitation of the present study is that only 6 animals were monitored for 30 days. The follow-up duration was not long enough; therefore, more extensive evaluation must clarify the effect of bilateral atrial appendage exclusion on ANP levels.

There are other limitations to this preclinical study. The study series was small (n = 14), and the follow-up period was only a maximum of 90 days. It is possible that there may be device failures or deployment complications with a longer follow-up or with application in patients whose tissues are less resilient than those of a healthy canine. In addition, animals were in sinus rhythm rather than AF.

Conclusions

The third-generation AED achieved easy, reliable, and safe exclusion of the LAA with favorable histologic results. Clinical application may provide a new therapeutic option for reducing the risk of stroke in patients with AF.

References

1. Wolf PA, Abbott RD, Kannel WB. Atrial fibrillation as an independent risk factor for stroke: the Framingham Study. *Stroke*. 1991;22:983-8.
2. Bleeding during antithrombotic therapy in patients with atrial fibrillation. The Stroke Prevention in Atrial Fibrillation Investigators. *Arch Intern Med*. 1996;156:409-16.
3. Hanna IR, Kolm P, Martin R, Reisman M, Gray W, Block PC. Left atrial structure and function after percutaneous left atrial appendage transcatheter occlusion (PLAATO): six-month echocardiographic follow-up. *J Am Coll Cardiol*. 2004;43:1868-72.
4. Meier B, Palacios I, Windecker S, Rotter M, Cao QL, Keane D, et al. Transcatheter left atrial appendage occlusion with Amplatzer devices to obviate anticoagulation in patients with atrial fibrillation. *Catheter Cardiovasc Interv*. 2003;60:417-22.
5. Nakai T, Lesh MD, Gerstenfeld EP, Virmani R, Jones R, Lee RJ. Percutaneous left atrial appendage occlusion (PLAATO) for preventing cardioembolism: first experience in canine model. *Circulation*. 2002;105: 2217-22.

6. Odell JA, Blackshear JL, Davies E, Byrne WJ, Kollmorgen CF, Edwards WD, et al. Thoracoscopic obliteration of the left atrial appendage: potential for stroke reduction? *Ann Thorac Surg.* 1996;61:565-9.

7. Sievert H, Lesh MD, Trepels T, Omran H, Bartorelli A, Della Bella P, et al. Percutaneous left atrial appendage transcatheter occlusion to prevent stroke in high-risk patients with atrial fibrillation: early clinical experience. *Circulation.* 2002;105:1887-9.

8. Kamohara K, Fukamachi K, Ootaki Y, Akiyama M, Cingoz F, Ootaki C, et al. Evaluation of a novel device for left atrial appendage exclusion: the second-generation atrial exclusion device. *J Thorac Cardiovasc Surg.* 2006;132:340-6.

9. Kamohara K, Fukamachi K, Ootaki Y, Akiyama M, Zahr F, Kopcak MW Jr, et al. A novel device for left atrial appendage exclusion. *J Thorac Cardiovasc Surg.* 2005;130:1639-44.

10. Kamohara K, Popovic ZB, Daimon M, Martin M, Ootaki Y, Akiyama M, et al. Impact of left atrial appendage exclusion on left atrial function. *J Thorac Cardiovasc Surg.* 2007;133:174-81.

11. Almahameed ST, Khan M, Zuzek RW, Juratli N, Belden WA, Asher CR, et al. Left atrial appendage exclusion and the risk of thromboembolic events following mitral valve surgery. *J Cardiovasc Electrophysiol.* 2007;18:364-6.

12. ACC/AHA guidelines for the management of patients with valvular heart disease. A report of the American College of Cardiology/American Heart Association. Task Force on Practice Guidelines (Committee on Management of Patients with Valvular Heart Disease). *J Am Coll Cardiol.* 1998;32:1486-588.

13. Schneider B, Stollberger C, Sievers HH. Surgical closure of the left atrial appendage—a beneficial procedure? *Cardiology.* 2005;104: 127-32.

14. Su P, McCarthy KP, Ho SY. Occluding the left atrial appendage: anatomical considerations. *Heart.* 2007 May 8 [Epub ahead of print].

15. Donnino R, Tunick PA, Kronzon I. Left atrial appendage thrombus outside of a "successful" ligation. *Eur J Echocardiogr.* 2009;9:397-8. Epub 2007 Mar 19.

16. Gillinov AM, Pettersson G, Cosgrove DM. Stapled excision of the left atrial appendage. *J Thorac Cardiovasc Surg.* 2005;129:679-80.

17. DiSesa VJ, Tam S, Cohn LH. Ligation of the left atrial appendage using an automatic surgical stapler. *Ann Thorac Surg.* 1988;46:652-3.

18. Rodeheffer RJ, Naruse M, Atkinson JB, Naruse K, Burnett JC Jr, Merrill WH, et al. Molecular forms of atrial natriuretic factor in normal and failing human myocardium. *Circulation.* 1993;88:364-71.

19. Stollberger C, Schneider B, Finsterer J. Elimination of the left atrial appendage to prevent stroke or embolism? Anatomic, physiologic, and pathophysiologic considerations. *Chest.* 2003;124:2356-62.

20. Yoshihara F, Nishikimi T, Kosakai Y, Isobe F, Matsuoka H, Takishita S, et al. Atrial natriuretic peptide secretion and body fluid balance after bilateral atrial appendectomy by the maze procedure. *J Thorac Cardiovasc Surg.* 1998;116:213-9.

21. Nakamura M, Niinuma H, Chiba M, Ueshima K, Arakawa N, Yagi Y, et al. Effect of the maze procedure for atrial fibrillation on atrial and brain natriuretic peptide. *Am J Cardiol.* 1997;79:966-70.

ET