Endoscopic Exposure and Stabilization of Posterior and Inferior Branches Using the Endo-Starfish Cardiac Positioner and the Endo-Octopus Stabilizer for Closed-Chest Beating Heart Multivessel CABG: Hemodynamic Changes in the Pig

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Background—Closed-chest, off-pump, multivessel CABG requires modified instruments to expose and stabilize posterior and inferior coronary branches. Using three new prototype devices, we explored the feasibility of endoscopic bypass grafting on these branches and assessed cardiac function during cardiac displacement.

Methods—Eight pigs (75 to 85 kg) were instrumented for hemodynamics and paced at 80 to 100 bpm. After closure of the sternotomy wound, the Da Vinci endoscope was inserted subxiphoidally. A sternal hook was used to hoist the sternum ventrally by 5 cm. The articulating EndoStarfish cardiac positioner was placed through a trocar (Ø12 mm). The positioner was fixed to the apex using –400 mm Hg suction and the heart was displaced anteriorly to 90 degrees. In 12 other pigs (75 to 85 kg), both internal mammary arteries (IMA) were harvested and the sternal wound was closed. Five trocar ports were placed for instrumentation (Ø12 mm, two in left chest, two in right chest, and one subxiphoidally). For coronary stabilization, a novel deployable EndoOctopus cardiac stabilizer was employed (suction –400 mm Hg). The Da Vinci robot-telemanipulator system was used for endoscopic grafting of the left and right IMA on posterior and inferior branches (16 anastomoses).

Results—When circumflex arteries were fully exposed and accessible for coronary surgery, stroke volume decreased by 18%±3 versus baseline (P=0.02) and mean arterial pressure decreased by 27%±6 (P=0.001). Additional 10 degrees Trendelenburg head-down positioning normalized stroke volume and arterial pressure. In the displaced heart, obtuse marginal branches (OM) and the ramus descendens posterior (RDP) of the right coronary artery became fully exposed with a mean arterial pressure >70 mm Hg during grafting. No accidental detachment occurred. Coronary target motion was restrained to approximately 1×1 mm. In two test cases, five sham distal anastomoses were created (grafts sewn to epicardium, left IMA to OM2 jump to OM3, right IMA to RDP, and composite graft from left IMA jump to diagonal branch). In 10 animals, 16 successfully completed anastomoses to RPD and OM branches of Ø1.75 to 2.5 mm required 25 to 60 minutes each to construct. At sacrifice, all anastomoses were patent.

Conclusion—In the closed-chest pig in Trendelenburg position and during lifting of the sternum, the EndoStarfish and EndoOctopus enabled IMA grafting of posterior and inferior branches on the beating heart without mean arterial pressure dropping below 70 mm Hg. (Circulation. 2003;108[suppl II]:II-34-II-38.)

Key Words: surgery ■ bypass ■ hemodynamics ■ coronary disease ■ minimal invasive
artery (CX). The left internal mammary artery (LIMA) and the right internal mammary artery (RIMA) served as grafts. To achieve endoscopic displacement and stabilization, Utrecht-designed modifications were used of the Starfish cardiac positioner, EndoStarfish, and Octopus tissue stabilizer, respectively, as well as a novel, Utrecht-designed sternum lift.

The secondary objective was to assess the hemodynamic consequences of closed-chest dislocation and stabilization of the beating heart.

Materials and Methods
Twenty Dutch landrace pigs (75 to 85 kg) were used. All animals received human care in compliance with the Guide for the Care and Use of Laboratory Animals published by the National Institutes of Health (NIH publication 85-23, revised 1985). The study protocol was approved by the Animal Experimentation Committee of the Utrecht University.

Anesthesia and Instrumentation
The pig was premedicated and anesthetized as previously described.9 First, midsternotomy was performed to allow easy instrumentation for hemodynamic measurements and time saving open-chest harvesting of the internal mammary arteries. After sternal closure, the amount of retrosternal working space was comparable with the space created after endoscopic dissection of mediastinal tissue and opening of the pleural spaces as performed in pilot studies. To create approximately 5 cm more space in the chest cavity ventrally, a novel design sternum lift was employed (Fig. 1).

Hemodynamic Measurements
In eight pigs, catheter-tip manometers (pressure independent of body position, Millar Instruments, Houston, TX) were inserted as previously described.9–11 After the administration of propranolol (range, 15 to 25 mg), pacing at a fixed rate of 80 to 100 bpm was started. An ultrasound transit time flow probe (Transonic Inc, Ithaca, NY, size 20 or 24 mm) was placed around the aorta for online measurement of the cardiac output (CO) as previously described.9 Stroke volume (SV) was calculated by dividing CO by the heart rate.

The Da Vinci robot-telemanipulator (Intuitive Surgical, Sunnyvale, CA) was used for both endoscopic visualization and manipulation. For the stereoscopic endoscope, subxiphoidal port access was used (port diameter, 13 mm). The EndoStarfish (Fig. 2) that had been modified from a regular Starfish cardiac positioner

Endoscopic Coronary Bypass Grafting
In 12 other pigs, both internal mammary arteries were harvested and the sternal wound was closed. Five trocar ports were placed (Ø12 mm, two in the left chest (3rd and 5th i.c. spaces), two in the right chest (3rd and 5th i.c. spaces), all in the midclavicular line, and one subxiphoidally). For displacement, the EndoStarfish (Fig. 2) was fixed to the free apicoanterolateral wall via the left upper access port, and fixed to the operating table rail. A novel, deployable EndoOctopus tissue stabilizer, also fixed to the operating table rail like the original Octopus, was introduced through the right upper trocar for local cardiac wall immobilization (Fig. 3). The Da Vinci end-effectors were introduced through the right and left lower trocar ports.

In two animals, sham distal anastomoses were created to test graft length (distal IMA grafts sewn to epicardium without opening the...
coronary artery, ie, LIMA with jump graft to OM2–3, RIMA to RDP, and composite graft from left IMA to jump diagonal 1 to LAD).

In ten animals, a total of 16 anastomoses were constructed to RPD and to OM branches (1.75 to 2.5 mm diameter). The RIMA was grafted to the RPD (n=3) and to the OM3 (n=3). Both RPD and OM3 were grafted using RIMA and LIMA, respectively (n=2). The LIMA was jump-grafted to the OM2/3 (n=2). In the same animal, the RIMA was grafted to the RDP.

The coronary stenosis was simulated by permanently occluding the proximal recipient coronary artery by a hemostatic clip. After making the arteriotomy, a microvascular bulldog clamp was used to eliminate backflow. The beveled distal end of the graft was first tagged to the coronary arteriotomy rim, whereafter a running 7-0 monofilament continuous suture was used to complete the anastomosis.

Experimental Protocol

The experimental protocol to assess hemodynamic changes on cardiac displacement was virtually identical to earlier open-chest studies.9–11 In brief, baseline cardiovascular values were recorded after stabilization in the anatomic position after at least 15 minutes of pacing (phase 1, baseline anatomic position). Subsequently, values were taken three (phases 2 to 5) and 15 minutes (phase 6) after stabilization following each intervention. In phase 2, the EndoStarfish was fixed to the apex while the heart remained in its anatomic position (FIX). In phase 3 (displacement to expose the proximal recipient coronary artery, DIS-Cx), the beating heart was hoisted by the cardiac positioner until 90 degrees extraanatomic position relative to the spine was achieved (lap pointing ventrally). In phase 4, the EndoOctopus was attached to the epicardium adjacent to the proximal obtuse marginal coronary artery.

Subsequently, following stabilization of hemodynamics, the operating table was tilted 10 degrees in the head-down position (Trendelenburg maneuver, TREN) without changing the position of the heart relative to the body (phase 5). After return from Trendelenburg, the heart was released from the cardiac positioner and fell back into the pericardial cradle (phase 6).

For endoscopic coronary bypass surgery, the EndoOctopus was attached to the epicardium adjacent to the proximal LAD, its first diagonal branch, the OM or the RDP.

Statistical Analysis

Data in Table 1 are presented as the mean value ± standard deviation (SD, absolute values). Hemodynamic variables in the Results section and in Fig. 4 are depicted as the mean value ± standard error of the mean (SEM) of the percentage of protocol control values (the heart in anatomic position). Statistical analysis was performed using multivariate analysis of variance to assess the influence of changing the apex position from anatomic position into 90 degrees extraanatomic position relative to the spine. A paired Student’s t test was used to assess the modifying effect of Trendelenburg compared with control values (anatomic position, phase 1).

Results

All animals survived all procedures without the need to defibrillate or administer inotropic drugs. No inadvertent detachment of the heart from either one of the endoscopic suction devices occurred during the procedures. The hemodynamic consequences of closed-chest displacement and stabilization of the beating heart are summarized in Table 1 and Fig. 4.

Attachment of the EndoStarfish to the Apex (Phase 2)

Care was taken to avoid inclusion of the distal left descending coronary artery (LAD) in one of the suction cups of the cardiac positioner. Because of its added articulation, only a few seconds were required to maneuver the device in position and attach it to the apex. SV decreased to 96% ± 3% (P=0.046 and MAP decreased to 91% ± 3% (P=0.012).

Endoscopic Cardiac Retraction (Phase 3)

Displacement of the heart by the apical suction device was performed by first pulling the apex in the axial direction of the left ventricle, whereafter the suction device was moved ventrally and cranially at the same time. The maneuver resulted in a minor transient drop in MAP. The posterior aspect of the heart became fully exposed, which included excellent view on the circumflex artery and its branches, the

| Hemodynamic Changes on Closed-chest Cardiac Displacement and Coronary Stabilization |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
|                      | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 | Phase 6 |
|                      | BASE    | FIX     | P-value | DIS Cx | P-value | OCT Cx | P-value | +TREN | P-value | ANA     |
| SV mL                | 44±3    | 42±3    | 0.046   | 36±3   | 0.021   | 32±3   | 0.004   | 39±3   | 0.123   | 44±4    |
| MAP mm Hg            | 109±4   | 100±6   | 0.012   | 79±6   | 0.001   | 77±5   | 0.002   | 102±5  | 0.254   | 101±8   |
| CO L/min             | 3.8±3   | 3.7±3   | 0.049   | 3.2±3   | 0.017   | 2.8±2   | 0.006   | 3.4±3   | 0.148   | 3.8±3   |
| RVEDP mm Hg          | 2±1     | 2±1     | 0.016   | 4±1    | 0.020   | 5±1    | 0.005   | 9±1    | 0.002   | 2±1     |
| LVEDP mm Hg          | 4±1     | 4±1     | 0.882   | 6±1    | 0.076   | 8±1    | 0.042   | 13±1   | 0.006   | 5±1     |

Values are expressed as mean±standard deviation. BASE indicates anatomic position; FIX, EndoStarfish™ cardiac positioner fixed to the heart (−400 mm Hg suction); DIS Cx, 90 degrees vertical displacement exposing circumflex branch; OCT Cx, EndoOctopus attached to circumflex branch; TREN, Trendelenburg maneuver (10-degree head-down body positioning), ANA, return to anatomic heart position.

Data vs baseline, mean±SEM, at 3 minutes after maneuvers. Paired-samples t test.

Figure 4. Comparison of hemodynamics on vertical displacement of the beating porcine heart with the EndoStarfish™ cardiac positioner. Mean percentage of baseline values ± standard error of the mean. FIX, attachment EndoStarfish cardiac positioner; DIS Cx, exposure circumflex branch; OCT Cx, EndoOctopus attached to marginal branch; TREN, Trendelenburg maneuver (10°head-down body positioning). Compared with baseline: *P<0.05, **P<0.01, ***P<0.001.
distal RCA, the great cardiac vein, the coronary sinus, the inferior caval vein, and the left lower pulmonary vein.

In diastole, radial expansion of the left ventricle was observed. SV decreased to 82%±3% (P=0.021 versus baseline) at the expense of increased right and left ventricular preloads. MAP decreased to 73%±6% (P=0.001 versus baseline).

**Endoscopic Cardiac Stabilization (Phase 4)**

Additional attachment of the EndoOctopus and local wall stabilization marginally decreased SV and MAP (to 74%±5% (P=0.004) and 72%±5% (P=0.002), respectively. It took less than 2 minutes to maneuver and subsequently to fix the stabilizer to the coronary target site.

**Whole-Body Head-Down 10-Degree (Trendelenburg) (Phase 5)**

SV and MAP normalized at the expense of further increased ventricular preloads. Right ventricular end-diastolic pressure (RVEDP) increased to 9±1 mm Hg (P= 0.002) and left ventricular end-diastolic pressure (LVEDP) increased to 13±1 mm Hg (P=0.006).

**Return of the Table in the Horizontal Position, Release of the EndoOctopus, Replacement of the Heart in the Anatomical Position, and Release from EndoStarfish (Phase 6)**

SV, CO, and MAP normalized quickly.

**Endoscopic Coronary Bypass Surgery**

In the displaced heart, the OM branches and the RDP became fully exposed. Provided that 10 degrees Trendelenburg body position was employed prior to displacement, MAP was maintained >70 mm Hg during grafting. By hoisting the sternal bone, approximately 5 cm distance was gained between the anterior aspect of the heart and the sternal bone. This permitted unhindered manipulation of the heart with the suction positioner within the limits of the chest cage. For exposure of the circumflex branch, the heart was stowed maximally in the right pleural space.

Inside the chest, the deployable horse shoe of the EndoOctopus was easily placed on the heart by the robot end-effectors by grabbing heavy breaded sutures attached to the EndoOctopus. Coronary artery motion was restrained to about 1x1 mm which allowed successful anastomosis suturing with the aid of the Da Vinci system.

In the two test cases, LIMA and RIMA graft length was just sufficient to reach the target site for five sham distal anastomoses (grafts sutured to epicardium, LIMA jump graft to OM2–3, RIMA to RDP and composite graft from LIMA to diagonal and jump to LAD).

In ten animals, 16 successfully completed anastomoses to target vessel exposure. Occasionally, 1 to 2 cm change in epicardium. DoStarfish, even when the EndoOctopus was attached to the epicardium.

Guided by the online CO readings with the ultrasound aortic probe, the optimal apical position was selected for each target vessel exposure. Occasionally, 1 to 2 cm change in apical position could improve CO by 10% to 15%. Ninety degrees of ventral cardiac dislocation resulted in excellent closed-chest exposure of the backside of the heart with an 18% decrease in stroke volume and a 27% decrease in arterial pressure less than we observed earlier in during open-chest dislocation. Similar to open-chest dislocation, right ventricular preload was markedly enhanced suggesting right heart dysfunction that we attribute to compression of the thin-walled right ventricle by surrounding tissue. Because of its ability to adjust for different angles of approach, the novel Utrecht EndoOctopus was versatile in immobilizing the LAD, its first diagonal branch, the circumflex branches, and the distal RCA using only one access port (the right lower trocar). By employing the original Octopus method (ie, bench-vicing the stabilizer to the operating table rail), cardiac motion was restrained sufficiently to perform grafting on coronary vessels down to 1.5 mm in diameter.

As shown previously in open-chest displacement of the beating heart, the Trendelenburg maneuver produced normalization of stroke volume, cardiac output, and arterial pressure at the expense of further enhanced right and left ventricular preload pressure. Hemodynamics remained stable for more than 1 hour.

**Discussion**

The principal findings of the study were (1) hoisting the sternum created approximately 5 cm extra space, which was sufficient to allow maneuvering the EndoStarfish, EndoOctopus, and Da Vinci end-effectors without the need for CO2 insufflation of the chest cavity; (2) the EndoStarfish and EndoOctopus enabled closed-chest bypass grafting of the OM branches and the RPD on the beating heart; and (3) both devices elicited hemodynamic changes similar to their open-chest counterparts, but less pronounced.

**Work Space Expansion by ThoraLift**

In the pig, mechanically lifting the sternum obviated the need for CO2 insufflation that carries the risk of inadvertent displacement of the coronary target out of endoscopic view when the EndoOctopus detaches and intrathoracic CO2 pressure drops abruptly (personal communication G. Wimmer-Greinecker MD).

**Closed-Chest Cardiac Retraction and Coronary Stabilization**

Placement of the EndoStarfish cardiac positioner was facilitated by the added angulation of the neck at the remote part of the device. The angulation enabled target approach at a lower than 90-degree angle (Fig. 2). In practice, the positioner became attached just off-side the apex at the free anterior wall of the left ventricle. During cardiac repositioning, care was taken not to overstretch the heart in the long axis direction. All relevant coronary targets at the lateral, posterior, and inferior of the heart became accessible for surgery. We observed no accidental release of the heart from the EndoStarfish, even when the EndoOctopus was attached to the epicardium.

Three major objectives that enable off-pump endoscopic coronary surgery were achieved: (1) adequate exposure of all
target coronary segments; (2) hemodynamic stability during exposure of vessels located at the posterior and inferior side of the displaced heart; and (3) endoscopic coronary stabilization. In 10 animals, it proved feasible to create off-pump 14 end-to-side and 2 side-to-side anastomoses with arterial grafts on posterior and inferior branches. However, because of small vessel size, and extra time needed for endoscopic instrument changes and blood that obscured the arteriotomy, anastomosis construction required 25 to 60 minutes. We infer from these results that the use of automated coronary connectors may reduce endoscopic anastomosis construction time substantially and prove closed chest, off-pump, multivessel CABG to be feasible in a reasonable amount of time.

Limitations
Possibly because of experience in applying the Octopus since 1994, we did not encounter inadvertent detachment of either EndoStarfish or EndoOctopus during these operations. There remains a risk, however, of loosing grip of the heart and jeopardizing completion of the anastomosis.

The pig’s chest cavity conformation is far more cartilaginous and ‘carinad’ shaped compared with the barrel-shaped human chest wall. The apex of the porcine heart is oriented somewhat right from the midline. Despite these anatomic differences, inferences on hemodynamic changes with open-chest cardiac displacement made from previous porcine studies appeared to be largely applicable to coronary patients. It remains to be determined whether the current endoscopic observations may be extrapolated to coronary patients as well.

Conclusions
In the closed-chest pig in Trendelenburg position, sternal lift, EndoStarfish and EndoOctopus enabled IMA grafting of posterior and inferior branches on the beating heart. During the entire procedure, arterial pressure remained above 70 mm Hg without the use of inotropic agents.

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