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Incidence and treatment of procedural cardiovascular complications associated with trans-arterial and trans-apical interventional aortic valve implantation in 412 consecutive patients☆,☆☆

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Abstract

Objective: Trans-catheter aortic valve implantation (TAVI) technology is rapidly evolving, with 412 procedures having been performed at our institution. Herein, we report a complete, prospective analysis of complications occurring during transvascular and trans-apical implantations with two different prostheses. **Methods:** Between June 2007 and June 2010, 412 patients (258 female, mean age 80.3 ± 7.2 years, logistic EuroSCORE (European System for Cardiac Operative Risk Evaluation) 20.2% ± 13.0%) underwent TAVI through either a retrograde (n = 252 transfemoral, n = 28 transaxillary, and n = 5 transaortic) or antegrade (n = 127 trans-apical) approach at our institution. The trans-apical access was chosen only in cases where transvascular implantation was not possible. As many as 283 CoreValve and 129 Edwards Sapien prostheses were implanted. **Results:** Thirty-day survival was 90.9%. Vascular complications occurred in 42 patients (10.2%). In four patients, lethal aortic root (n = 3) or abdominal (n = 1) aortic rupture occurred. Pericardial effusion developed in 53 patients (12.8%), which resulted in cardiac tamponade in 12 patients (2.9%). Twenty-three patients (5.6%) with valve malplacement were treated interventionally. In five patients (1.2%), emergency institution of cardiopulmonary bypass was required during the procedure for temporary support; all patients survived. Seventeen patients underwent re-intervention on the catheter valve (4.1%). **Conclusions:** With growing experience, complications with TAVI may be avoided by proper patient selection and skillful management. Other complications, when they occur, require a specific treatment algorithm to avoid delay in decision making. A considerable number of complications after TAVI require surgical treatment. Therefore, the ideal environment for TAVI procedures is a hybrid operating room, where a multidisciplinary team of surgeons, cardiologists, and anesthesiologists is best fitted to meet the current needs associated with TAVI technology. A reduction in complications was seen after 300 cases. This finding attests to the complexity of the procedure in addition to the experience required to reduce the incidence of complications.

Keywords: Trans-catheter aortic valve implantation; Cardiovascular complication; Learning curve

1. Introduction

Trans-catheter aortic valve implantation (TAVI) is a novel therapeutic option for high-risk patients with aortic stenosis. Since Cribier [1] performed the first-in-man trans-catheter implantation of an aortic valve substitute in 2002, the technique has been further developed and has entered daily routine in some centers. The target population for TAVI are elderly patients with severe co-morbidities and an increased risk for surgical aortic valve replacement (SAVR) [2,3]. Technical feasibility has been proven by several groups [4–7], though the incidence and management of procedure-related complications remain a field of current investigation. The trans-catheter treatment is associated with complications different from other catheter procedures and from SAVR. The present study systematically reviews the incidence and management of procedure-related cardiovascular complications after 412 cases from a group performing retrograde arterial and antegrade transapical TAVI by an interdisciplinary team in a hybrid suite. In addition, algorithms for the prevention and management of those complications are provided, which were obtained during the learning curve.

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2. Methods

Between June 2007 and June 2010, we prospectively collected the data of 412 patients undergoing TAVI via either a trans-arterial or trans-apical approach at the German Heart Center, Munich. During this time, 283 CoreValve and 129 Edwards Sapien prostheses were implanted. The access-site approach and patient characteristics are summarized in Table 1.

2.1. Patient selection, preoperative evaluation, and choice of access site

Symptomatic patients with severe aortic stenosis deemed either high risk or inoperable for SAVR were considered for trans-catheter valve implantation. Clinical judgment in conjunction with surgical risk score estimates (specifically, the logistic EuroSCORE (European System for Cardiac Operative Risk Evaluation) and Society of Thoracic Surgeons (STS) score) provided the basis for identification of high-risk patients. Informed consent was obtained from all patients. The local ethics committee approved the study (2234/08).

All patients underwent computed tomography of the thorax, abdomen, and pelvis with three-dimensional (3D) reconstructions of the arterial vasculature and aortic root. Coronary angiography was used to assess for coronary artery disease. Percutaneous revascularization, if required, was performed in a staged manner prior to TAVI (median time to TAVI: 55 days (2–141 days)). In all patients, the annulus

Table 1. Characteristics and implanting routes of 412 patients who underwent TAVI.

Variable	*N* (% of 412) or mean ± SD	Retrograde (*n* = 285)	Antegrade (*n* = 127)	*p*
	283 (68.7%)	278 (97.5%)	5 (3.9%)	<0.001
CoreValve prosthesis	245	245	–	
Transfemoral	5	–	5	
Trans-apical	28	28	–	
Via subclavian artery	5	5	–	
Via ascending aorta				
Edwards Sapien prosthesis	129 (31.3%)	7 (2.5%)	122 (96.1%)	
Transfemoral	7	7	–	
Trans-apical	122	–	122	
Female gender	258 (62.6%)	153 (53.7%)	105 (82.7%)	<0.001
Age (years)	80.3 ± 7.2	80.3 ± 7.6	80.2 ± 6.2	0.87
Logistic EuroSCORE (%)	20.2 ± 13.0	20.0 ± 12.9	20.5 ± 13.3	0.74
STS score (%)	5.6 ± 3.6	5.5 ± 3.5	5.8 ± 3.7	0.54
NYHA III or IV	400 (97.0%)	274 (96.1%)	126 (99.2%)	0.11
Impaired ejection fraction	144 (36.6%)	107 (37.5%)	37 (29.1%)	0.001
35–50%	81	51	30	
<35%	63	56	7	
Porcelain aorta	26 (6.3%)	14 (4.9%)	12 (9.4%)	0.12
Aortic valve area (cm^2)	0.67 ± 0.20	0.68 ± 0.19	0.66 ± 0.22	0.45
Mean aortic gradient (mmHg)	47.9 ± 16.3	48.2 ± 16.5	47.1 ± 15.9	0.52
Mean BNP level (ng/dl)	6062 ± 12038	5680 ± 7674	7117 ± 19588	0.35
Coronary heart disease	221 (55.7%)	141 (49.5%)	77 (60.6%)	0.64
No intervention required	65	43	22	
Previous stent implantation	99	64	35	
Previous coronary artery bypass operation	57	34	20	
Previous cardiac surgery	77 (19.5%)	47 (16.5%)	30 (23.6%)	0.010
Coronary artery bypass	49	33	16	
Mitral/tricuspid valve repair or replacement	9	6	3	
Aortic valve replacement	6	–	6	
Combination/other	13	8	5	
Peripheral vessel disease	92 (23.3%)	41 (14.4%)	51 (40.2%)	<0.001
Stenosis > 70% or symptoms	75	32	43	
Previous stent implantation	6	3	3	
Previous surgery	11	6	5	
Cerebrovascular disease	96 (24.3%)	51 (17.9%)	45 (35.4%)	0.006
Stenosis > 70%	39	24	15	
Previous stent implantation	10	5	5	
Previous surgery	11	5	6	
Previous stroke, no stenosis	36	17	19	
Severe pulmonary hypertension (PAP > 60 mmHg)	91 (23.3%)	62 (21.8%)	29 (22.8%)	1.0
Renal insufficiency (creatinine level > 1.5 mg/dl)	71 (18.0%)	50 (17.5%)	21 (16.5%)	0.78
Atrioventricular valve lesions	62 (15.7%)	46 (16.1%)	16 (12.6%)	0.32
Mitral valve regurgitation > II	23	18	5	
Tricuspid valve regurgitation > II	27	18	9	
Mitral and tricuspid valve regurgitation > II	8	8	–	
Mitral stenosis	4	2	2	
Severe respiratory disease	79 (20.1%)	59 (20.7%)	20 (15.7%)	0.33
COPD	68	52	16	
Restrictive lung disease	11	7	4	

BNP: brain natriuretic peptide; COPD: chronic obstructive pulmonary disease; NYHA: New York Heart Association; PAP: pulmonary artery pressure; and STS: Society of Thoracic Surgeons.

diameter was measured by transthoracic and transesophageal echocardiography.

The transfemoral access route is evaluated as initial default strategy for all patients. To accommodate the 18-F Medtronic CoreValve delivery system, the minimum cut-off vessel diameter is 6.5 mm. On the other hand, the 22-F and 24-F Edwards Sapien delivery system requires a minimum vessel diameter of 7 and 8 mm, respectively. If the transfemoral route was not eligible (vessel diameter too small, severe tortuosity, and previous peripheral bypasses or stents), we sequentially evaluated the subclavian, transapical, and ascending aorta for access.

2.2. Implantation techniques

Details of the device and technical aspects of the procedure have been previously published [4,6,8–10]. Briefly, all patients were operated in a surgical hybrid suite by an interdisciplinary team consisting of surgeons, cardiologists, and anesthesiologists. In the first 174 patients treated transfemorally, we opted to perform the procedures under general anesthesia to assure stable hemodynamics and avoid patient movement during valve implantation. More recently, we started to perform transfemoral implantations under light sedation ($n = 65$). As an added safety precaution, arterial and venous guide wires were placed into one groin at the beginning of the procedure in anticipation for the need of femoral–femoral bypass. Transfemoral valve implantation was performed either by percutaneous puncture and device closure (ProStar XL, Abbott Vascular, IL, USA; $n = 167$) or by surgical cut-down of the femoral artery ($n = 85$). Subclavian access was obtained by surgical cut-down ($n = 28$). Antegrade TAVI was performed through a left anterolateral minithoracotomy ($n = 127$). In five patients, retrograde implantation through the ascending aorta was performed through a partial upper ministernotomy. A transient pacemaker wire was placed either transvenously or epicardially during trans-arterial and trans-apical valve implantation, respectively.

2.3. Definition of end points

For the purposes of this study, we documented the following intraprocedural cardiovascular end points:

(1) Intraprocedural hemodynamic compromise (cardiac depression): Any considerable blood pressure drop during the procedure that required catecholamines, cardiopulmonary resuscitation, defibrillation, or the institution of cardiopulmonary bypass.
(2) Vascular injury: Minor and major vascular injury is reported according to the Valve Academic Research Consortium (VARC) criteria [11] and includes any thoracic aortic dissection or access-site- or access-related vascular injury (dissection, stenosis, perforation, rupture, arteriovenous fistula, pseudo-aneurysm, hematoma, irreversible nerve injury, or compartment syndrome) leading to either death, need for significant blood transfusions ($\geq$4 units), percutaneous or surgical intervention, or irreversible end-organ damage (e.g., hypogastric artery occlusion causing visceral ischemia or spinal artery injury causing neurologic impairment), or distal embolization (non-cerebral) from a vascular source requiring surgery.
(3) Prosthesis malplacement: Any dislocation or embolism of the prosthesis during the implantation procedure.
(4) Pericardial effusion: Any new pericardial effusion identified either during or after the procedure by echocardiography.
(5) Coronary obstruction/myocardial infarction: Myocardial infarction is reported according to the VARC criteria [11] and includes new coronary obstruction documented by angiography or coronary obstruction that results in (a) new ischemic symptoms (e.g., chest pain or shortness of breath), (b) new ischemic signs (e.g., ventricular arrhythmias, new or worsening heart failure, new ST-segment deviations – either elevation $>$1 mm or depression $>$1 mm in two or more contiguous leads, hemodynamic instability, or imaging evidence of new loss of viable myocardium or new wall motion abnormality), and (c) confirmatory biomarker evidence, consisting of two or more samples for creatinine kinase-MB (CK-MB) that are 6–8 h apart with a 20% increase in the second sample and a peak value exceeding 10$\times$ the 99th percentile upper reference limit (URL) or a peak value exceeding 5$\times$ the 99th percentile URL and with new pathological Q waves in at least two contiguous leads. Mechanical coronary artery obstruction may result from (i) impingement of the coronary ostia by the valve support structure in the setting of suboptimal valve positioning; or (ii) embolization from calcium, thrombus, air, or endocarditis; or (iii) displacement of native aortic valve leaflets toward the coronary ostia (during TAVI).
(6) Re-intervention: The need for either trans-catheter (specifically, valve-in-valve) or SAVR for clinically significant valve malfunction (e.g., central or paravalvular aortic regurgitation).

2.4. Data collection and statistical analysis

Patients' baseline characteristics, intraprocedural data and postprocedural complications were prospectively recorded in a computerized database. Continuous variables are presented as means ($\pm$SD). Categorical variables are presented as frequencies and percentages. Differences between trans-arterial and trans-apical groups were analyzed by unpaired Student's t-tests (continuous variables), chi-square tests, or Fisher's exact tests (dichotomous or nominal variables), as appropriate. Kaplan–Meier survival estimates were performed for patients with and without complications and compared with the log rank test. Statistical significance was set at a 0.05 probability level. All statistical analyses were performed with Statistical Package for Social Sciences (SPSS) 16.0 German.

3. Results

Thirty-day, 6-month, and 1-year survival were 90.9%, 78.9%, and 77.4% without differences between access routes (see survival curve, Fig. 1). In-hospital mortality was 12.9%. Table 2 summarizes the intra- and periprocedural complica-

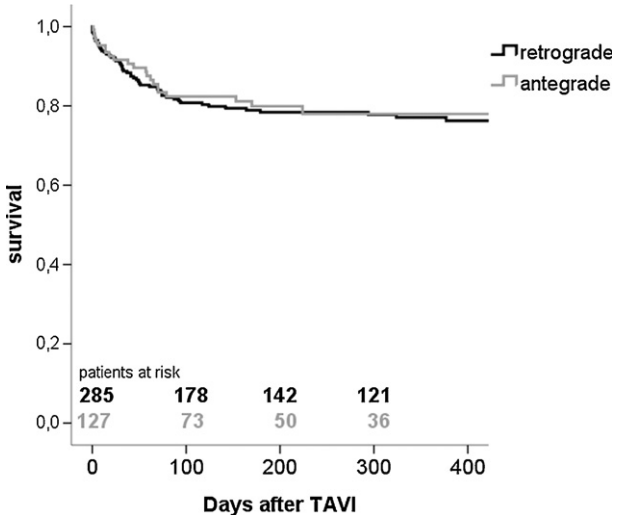

Fig. 1. Survival curve after trans-catheter aortic valve implantation (TAVI). Black line: retrograde access, gray line: antegrade access; 6-month and 1-year survival were 78.4% and 77.1% (retrograde) versus 79.9% and 78.0% (antegrade), $p = 0.74$. Follow-up duration is shown in days on the *x*-axis.

Table 2. Summary of complications with respect to implanting route.

	Implanting route		
	Trans-arterial ($n = 285$)	Trans-apical ($n = 127$)	*p*
Aortic rupture	3 (1.1%)	1 (0.8%)	0.80
Femoral complication	33 (11.0%)	0	<0.001
Prosthesis malplacement	23 (8.1%)	0	0.001
Intraprocedural cardiac depression (with resuscitation)	16 (5.6%)	10 (7.9%)	0.38
Pericardial tamponade	9 (3.2%)	3 (2.4%)	0.66
Re-intervention on catheter valve	12 (4.2%)	5 (3.9%)	0.90
Coronary ischemia	5 (1.8%)	3 (2.4%)	0.68

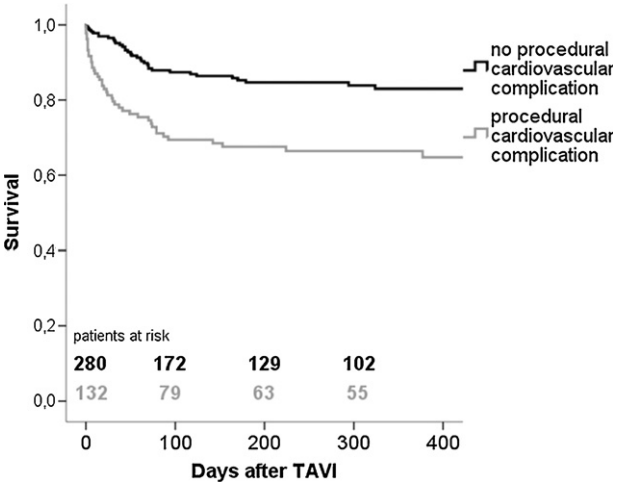

Fig. 2. Survival curve after trans-catheter aortic valve implantation. Black line: no cardiovascular complications, gray line: procedural cardiovascular complications; 6-month and 1-year survival were 84.7% and 83.0% (no complications) versus 67.4% and 66.2% (with occurrence of cardiovascular complications), $p < 0.001$. Follow-up duration is shown in months on the *x*-axis.

tions that occurred in our patient population with respect to the access site for implantation. Patients without occurrence of procedural cardiovascular complications had a significantly better survival (30 days, 6 months, and 1 year: 96.5%, 84.7%, and 83.0% vs 79.5%, 67.4%, and 66.2% in patients with complications, $p < 0.001$, see Fig. 2).

3.1. Intraprocedural cardiac depression

Intraprocedural cardiac depression occurred in 75 cases. A total of 49 patients could be stabilized with catecholamine treatment alone. In 21 patients, successful cardiopulmonary resuscitation (CPR) was performed. In four of those patients, additional defibrillation was necessary. Immediate installation of cardiopulmonary bypass was required in five patients. All could be weaned successfully after hemodynamic stabilization.

3.2. Vascular complications

Vascular complications occurred in 42 patients (10.2%).

Rupture of the ascending aorta occurred in three patients. In one of these cases, ascending aortic rupture occurred upon trans-apical delivery of an Edwards Sapien prosthesis and immediate conversion to median sternotomy ensued. In the other two cases, delayed ascending aortic rupture occurred following the implantation of a Medtronic CoreValve prosthesis 27 and 24 h after the initial procedure, respectively. Delayed lethal rupture of the descending aorta occurred in a patient with a previously stent-treated abdominal aneurysm 4 h after a Medtronic CoreValve implantation. A clinically unapparent descending aortic dissection was treated conservatively.

Complications from the femoral access site were observed in 33 patients ($n = 2$ Sapien, $n = 31$ CoreValve, 13.1% of 252 transfemorally treated patients). Three patients underwent implantation of a covered stent for vessel rupture. In 12 patients, surgical suture of the vessel leakage was performed, and five patients required surgical interposition of a vascular prosthesis. Twelve patients underwent surgical revision for hematoma, embolism, vessel occlusion, or false aneurysm. There were significantly less femoral access-site complications (5/85, 5.9%), if the femoral artery was dissected free as compared with the use of a vessel closure device (28/167, 16.8%, $p = 0.015$).

One patient experienced subclavian artery injury during a CoreValve implantation and the vessel was repaired by interposition of a vascular prosthesis. Another patient showed asymptomatic subclavian artery dissection after CoreValve implantation.

Two patients experienced radial artery dissection or rupture after insertion of the sheath for pigtail placement ($n = 2$ transfemoral CoreValve). Both underwent surgical fasciotomy of the arm.

3.3. Prosthesis malplacement

Prosthesis malplacement did not occur with the Edwards Sapien prosthesis, but in 23/283 patients (5.6%) treated with a CoreValve prosthesis. In 19 patients, a partially deployed Medtronic CoreValve prosthesis dislocated into the ascending

aorta. All patients could be treated by retrieval of the partially deployed prosthesis through the introducer sheath and *de novo* placement after crimping the same prosthesis again onto the deployment catheter. In four patients, a completely deployed CoreValve prosthesis dislocated into a supra-annular position. In all of these patients, the prosthesis could be retracted with a 'goose-neck' catheter into the ascending or descending aorta, and a second prosthesis was implanted intraannularly.

3.4. Pericardial effusion

A total of 53 patients showed postprocedural pericardial effusion, of whom 12 developed pericardial tamponade.

In 42 patients, echocardiographic evidence of pericardial effusion was <1 cm. All underwent meticulous echocardiographic monitoring during the postoperative stay. Three of those developed cardiac tamponade 3 h, 2, and 3 days after the procedure and received uneventful pericardial puncture.

Eight of 11 patients with echocardiographic signs of pericardial effusion >1 cm exhibited immediate hemodynamic impairment and underwent subxiphoid puncture ($n = 4$) or sternotomy ($n = 4$), respectively, in the hybrid suite. In the patients who underwent sternotomy, perforation of the left-ventricular myocardium by the wire was found to be a source of bleeding. The other three patients were transferred to the intensive care unit without immediate intervention, one of them requiring sternotomy 2 h postoperatively for cardiac tamponade.

3.5. Coronary ischemia

In eight patients (1.9%), signs of coronary ischemia developed. In one patient, a dislocated valve occluded the right coronary ostium (transfemoral CoreValve), which was resolved successfully by retraction of the prosthesis. Another patient (trans-apical Sapien) developed lethal left anterior descending (LAD) artery thrombosis. In three patients, native aortic valve calcium obstructed the left main stem after implantation of a Medtronic CoreValve ($n = 1$) or an Edwards Sapien ($n = 2$) prosthesis, respectively. The patients were treated by surgical removal of the prosthesis and SAVR, coronary artery bypass grafting, and left main stenting. Two patients showed elevated cardiac markers postoperatively due to unknown reasons. One patient with postoperative ventricular fibrillation and emergent cardiac catheterization underwent stenting of an embolic RCA occlusion and recovered without residuals.

3.6. Re-intervention for valve malfunction

An intervention on the implanted catheter valve was required in 17 patients (4.1%).

Due to hemodynamically relevant central or paravalvular regurgitation, seven patients (1.7%) underwent a valve-in-a-valve implantation ($n = 3$ transfemoral Medtronic CoreValve, $n = 4$ trans-apical Edwards Sapien) during the initial procedure. In six patients with a Medtronic CoreValve, clinically significant central or paravalvular regurgitation developed postoperatively and these patients were also treated with a valve-in-a-valve procedure 2 days to 3 months after the initial procedure. In three other patients with progressively increasing paravalvular leakage, a Medtronic CoreValve prosthesis was replaced by SAVR. One patient had clinically significant central regurgitation as a result of a trapped Sapien leaflet by native valve tissue and underwent surgical excision of the native aortic valve leaflet.

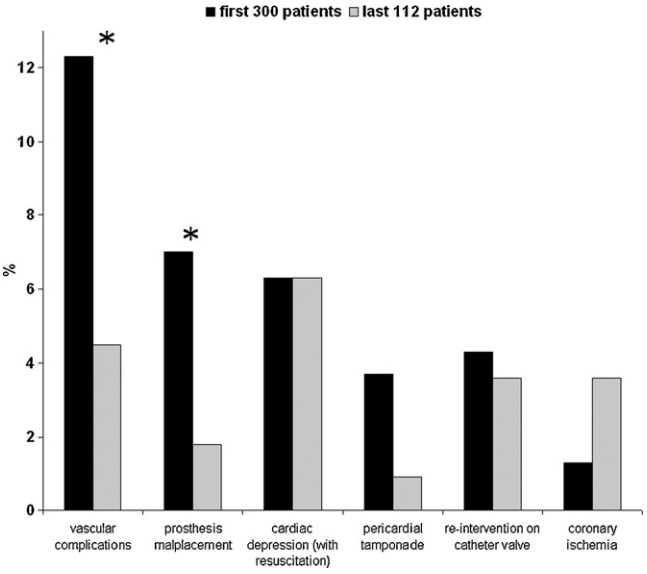

Fig. 3. Incidence of the reported complications (vascular complications, prosthesis malplacement, cardiac depression with resuscitation, pericardial tamponade, re-intervention on the catheter valve, and coronary ischemia) during the first 300 cases (black bars) and the last 112 cases (gray bars). A significant reduction in the incidence of complications was seen for vascular complications (from 12.3% to 4.5%, $p = 0.019$) and for prosthesis malplacement (from 7% to 1.8%, $p = 0.040$).

3.7. Learning curve

The frequency of any complication decreased from 38% in the first 300 patients to 17% in the last 112 patients ($p < 0.001$) (Fig. 3). More specifically, vascular complications decreased from 12% to 4.5% ($p = 0.019$) and prosthesis malplacement decreased from 7% to 2% ($p = 0.040$). There was no change in the incidence of cardiac depression, cardiac tamponade, re-intervention, or coronary ischemia.

4. Discussion

Trans-catheter aortic valve treatment is associated with complications different from other catheter procedures and different from complications following SAVR. During our learning curve, algorithms for the prevention and management of these complications were developed.

4.1. Vascular complications

Acute or delayed aortic root rupture is a rare but serious complication (<1% in our series) that may occur after balloon valvuloplasty or after valve implantation, especially in elderly women with fragile tissue where bulky calcifications may perforate the aortic root. Other groups describe

individual cases of aortic root rupture [12], or ascending aortic dissection [12,13]. The prognosis is usually poor, even if emergent open surgical repair is performed [12,13]. Naturally, preoperative meticulous annulus measurements by computed tomography (CT) scan and echocardiography are mandatory to avoid oversizing of the balloon or prosthesis. In our own series, this serious complication occurred exclusively in the early period of our implantation experience, without having a clear explanation for this finding.

Peripheral vessel rupture, dissection, or bleeding requiring interventional or surgical treatment occurred in 13.1% of the 252 transfemorally treated patients in our patient population, and is described in 7–20% of the cases by other groups [4,14–19] with population sizes of only 10–50 patients. These early reports do not suggest a considerable difference between the two valve types. Our data demonstrate a significant reduction of vascular access-site complications with a surgical cut-down compared with a vessel closure device. We therefore refined our percutaneous technique and perform the puncture of the access site only after crossing a pigtail catheter from the contralateral femoral artery, which serves to hit the artery in its central portion. Before removal of the femoral sheath, a Terumo wire is again crossed from the contralateral artery for potential balloon insertion, if the closure device fails. In very obese patients or in patients with severe calcifications, we opt for a surgical cut-down.

Furthermore, we caution against choosing the transfemoral access in patients with previous iliac- or aortic-stent implantation, as one patient in our series experienced descending aortic rupture at the site of a previously implanted abdominal aortic stent.

4.2. Prosthesis malplacement

The management of prosthesis dislocation requires highly skilled catheter expertise and emergent surgery in some cases. The incidence of Medtronic CoreValve dislocation was 5.6% in our series (23/283). Literature data are rare, with only one other group reporting an incidence of 3% [20]. Dislocation of the Edwards Sapien prosthesis has been reported to occur in 4–11% in five series [4,6,12,18,21], whereas our group did not experience this complication. Reasons for dislocation of a partially deployed CoreValve prosthesis are instability in the aortic root during deployment due to severe regurgitation after balloon valvuloplasty, unfavorable angulation, and thoracic or abdominal aortic kinking, which may lead to uncontrollable movements at the implantation site following manipulations from the groin. We now exclude patients with more than mild thoracic or abdominal kinking from transfemoral TAVI. To improve stabilization of the valve during deployment, higher-rate ventricular pacing may be performed, especially in patients with aortic insufficiency. Alternatively, the subclavian artery access may be chosen. A completely deployed Medtronic CoreValve prosthesis may also dislocate accidentally after successful deployment by retraction of the delivery system if the anchors are not fully released from the deployment catheter, or if the tip of the deployment catheter gets caught at the proximal end of the prosthesis. This is prevented by reassurance that both anchors are released, which may sometimes require the exact exposure of the anchors in different imaging levels. Furthermore, pulling on the intraventricular Amplatz super stiff wire centers the conical tip of the delivery system, which can then be removed without touching the proximal valve stent.

Dislocation of a partially or completely deployed Medtronic CoreValve or Edwards Sapien prosthesis into the ascending aorta can be managed interventionally in most cases, as described above. Both valves are at risk for dislocation if either the annulus is too large, or secondary intraprocedural dilation of the implanted prosthesis is performed, or rapid pacing is terminated too early. Thus, meticulous annulus measurements by echocardiography and CT are paramount, and rapid pacing should be stopped only after complete deflation of the balloon during secondary dilation of the already deployed valve. Embolization of the Edwards Sapien prosthesis into the ventricle has been described to occur under circulatory support with the heart–lung machine with retrograde perfusion from the femoral artery. This complication may only be treated surgically.

4.3. Cardiac depression

Cardiac depression with a considerable decrease of blood pressure requiring resuscitation occurred in 6.3% (26/412) of the cases in our series. Other groups describe individual cases [17], or incidences of emergent installation of extracorporeal bypass in 12–25% [12,21], and ventricular fibrillation in 4–11% [4,18]. Some minor cardiac depression occurs usually in most patients after rapid pacing for balloon valvuloplasty or after valve deployment, especially in patients with predisposing conditions, such as impaired left-ventricular function, severe myocardial hypertrophy, or severe pulmonary hypertension. In patients with an extremely reduced valve-opening area, the delivery system in the annulus may even cause subtotal obstruction. In these cases, relatively fast deployment with relief of the obstruction is paramount. To prevent circulatory depression, it is recommended to start with rapid pacing only if the systolic arterial pressure is above 100 mmHg.

In the majority of the patients, circulatory depression is successfully treated with administration of catecholamines alone. Resuscitation and the institution of extracorporeal circulatory support are necessary only in a minority of the cases. To facilitate emergent installation of extracorporeal bypass, arterial and venous guide wires may be placed in the groin prior to the procedure. As all of the five patients in the present series could be weaned successfully after emergent extracorporeal circulatory support, a standby heart–lung machine should be considered a standard of care for TAVI procedures. Depending on other causes of low cardiac output, therapy could include coronary angiography and intervention, pacing, or pericardial puncture.

4.4. Pericardial effusion

In the present series, periprocedural pericardial effusions occurred in 12.9% (53/412) of patients. In approximately a quarter of these patients, clinical signs of hemodynamically relevant tamponade developed (12/412, 2.9%). Data from

the literature reveal an incidence of pericardial tamponade in 2—8% [6,12,15,18,20,22]. The origins of a hemorrhagic pericardial effusion are multifactorial and they may occur promptly during valve implantation, or may be delayed. The source of bleeding may be the right ventricle, following perforation of the transient pacemaker wire. Perforation of the left ventricle may occur with a fixed core wire, or with the Judkins or multipurpose catheters after valve passage. Some preventive strategies may help to avoid these injuries: In addition to applying the usual precautions established in interventional cardiology, some measures are specific for TAVI procedures. Meticulous care should be taken to bend the tip of the Amplatz super stiff wire manually in an appropriate fashion prior to insertion into the left ventricle. A correct position of the guide wire within the left ventricle is crucial. The tip should be non-attached to the ventricular wall, and the curve of the wire should line the septum and apex within the cavity of the left ventricle.

As for the management of pericardial effusions, we have established the following algorithm for our institution: As a standard of care, all patients should undergo echocardiographic control for the identification of pericardial effusion at the end of the implantation procedure. Small effusions $<$10 mm without hemodynamic impairment are monitored echocardiographically at close intervals. Patients with rapidly increasing effusions and with effusions causing hemodynamic impairment (central venous pressure (CVP) increase, blood pressure decrease, and tachycardia) undergo pericardial puncture and insertion of a drain. If no improvement of the symptoms is achieved, emergent sternotomy is performed.

4.5. Myocardial ischemia

Coronary ischemia and cardiac marker elevation are seen in 0—27% [4,12,14—16,20,21,23] of patients after TAVI and occurred in 1.9% (8/412) of our patients from various reasons. Coronary ischemia due to a dislocated prosthesis is consequently treated by interventional retraction of the prosthesis. Left-main-stem obstruction by native valve calcium is rare [4,12] and requires surgical removal of the prosthesis, or may be treated with coronary artery bypass grafting or left main stem stenting in some cases [12]. Close inspection of the echocardiographic and CT images for unusual native leaflet excrescence might allow anticipation of this complication [12]. Thrombembolic coronary occlusion is treated interventionally. In all patients with clinically significant postoperative cardiac marker elevation, cardiac catheterization should be performed immediately.

4.6. Re-intervention on the catheter valve

Re-intervention may be required in cases of valve malfunction or high-degree paravalvular leakage. Only sparse data are available on the need for re-interventions after TAVI. In our series, surgical removal of a catheter valve and subsequent SAVR was required in cases of hemodynamically relevant paravalvular leakage. In the present series, intra-operative central or severe paravalvular leakage could be resolved by implantation of a second trans-catheter valve during the same procedure. This approach has been described also by Grube et al. [20] in 3/136 patients. An event not yet described in the literature occurred in six other patients of our series: delayed development of central or paravalvular regurgitation in a Medtronic CoreValve prosthesis up to 3 months after the initial procedure. All patients could be treated again interventionally by implantation of a second catheter valve. Close echocardiographic follow-up investigations are mandatory for the identification of this complication.

4.7. Learning curve

Our observation of a learning curve was based exclusively on the reduction of cardiac procedural complications. Based on the objectives of our study, other clinical end points such as mortality, stroke, and complete heart block were not analyzed in the context of a learning curve. A search for a learning curve was conducted at an interval of every 50 TAVI cases. Having said that, we noticed a reduction in complications only after 300 cases. This finding attests to the complexity of the procedure in addition to the experience required to reduce the incidence of complications. However, the fact that more than one operator was involved during establishment of the TAVI program at our center might have contributed to a longer learning curve.

5. Conclusion

TAVI is an exciting new technology that offers an alternative treatment for high or prohibitive surgical-risk patients with aortic stenosis. Although TAVI avoids the use of extracorporeal circulation and sternotomy, it is nonetheless associated with inherent complications. Some of the procedural complications may be attributed to a specific learning curve and thus be avoided in the future: aortic root rupture by precise measurement of the root diameters and by excluding patients with bulky calcifications, ventricular rupture by even more careful manipulation of the wires, prosthesis malplacement by avoiding patients with unfavorable aortic anatomy, peripheral vessel injury by seeking alternative access sites, considerable intraprocedural cardiac depression by meticulously maintaining sufficient intraprocedural perfusion pressure and respect time for myocardial recovery, just to mention a few. Other complications require a specific treatment algorithm to avoid time delay for decision making when they occur. In addition, a highly specialized and motivated team with excellent cooperational skills should perform all the implantations to circulate the experience gained.

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Appendix A. Conference discussion

Dr F. Casselman (*Aalst, Belgium*): This is a large series dealing with everyday complications and it is very important that such manuscripts are submitted because they are extremely instructive to all of us performing transcatheter procedures. I will stick to two short questions.

First of all, you showed us the treatment of some endovascular complications through the iliac access or femoral site. Were these complications dealt with by the cardiac surgeon, by the cardiologist, or did you call in a vascular surgeon, or do you routinely have a vascular surgeon present to deal with these complications? Secondly, given the experience with some complications throughout the study period, did you change your selection of delivery route? For example, did your percentage of transfemoral approach decrease in favor of transaxillary or trans-apical in view of potential complications? Did you become stricter about selecting the transfemoral route?

Dr Lange: In regard to your first question, our heart center does not have any vascular surgeons and all the complications were treated by cardiac surgeons. It is really not very difficult to put covered stents in the peripheral vessels; this is part of our daily work.

In regard to the complications and the learning curve, I agree that we have changed how we proceed, and we will keep on changing I think. We will not persist with transfemoral access if we have any doubts. If there is heavy calcification, marked tortuosity, then we go for the subclavian approach, and if this doesn't work we go for the trans-apical right away. We have also reduced the vascular complications considerably by just doing a surgical cut-down as opposed to using the closure device in each and every patient.

Dr M. Romano (*Massy, France*): I have just a short question concerning the coronary complication. When you have very bulky calcification of the leaflets on the native or prosthetic valve, don't you think that it might be advisable sometimes to put a protecting guidewire in the left main or right coronary artery, very close to the calcified valve, so as to be ready to place a catheter in the coronary and dilate and stent it very quickly?

Dr Lange: I know that this is performed in some centers. We have never tried it. It can be discussed. If you have this complication, the first thing you have to do is to put the patient on cardiopulmonary bypass, I think, to protect the circulation. Then it takes only a very short time to put a stent into the left main. But I agree that your suggestion could be considered.

Dr Romano: But when you have a complete occlusion, even if you put the patient on cardiopulmonary bypass, sometimes you might never be able to put a guidewire in a completely occluded coronary artery. If the guidewire is already in place, it is much easier to go inside there and place the stent. This is my opinion and my experience.

Dr Lange: The stenting I showed here was under cardiopulmonary bypass. That was not really a problem.

Dr T. Walther (*Bad Nauheim, Germany*): Very important data. An important point was made by the discussant. I think your approach is very nice as a team, and we all should not stay away or run out when there is a vascular complication. If we are surgeons and want to be part of this game, trans-catheter valves, we have to deal with the problems. If the team has a femoral complication, we don't call the vascular surgeons. We know how to stitch a femoral vessel. You made that very clear. I just want to emphasize that. I think it is very important that we are part of the whole game, to stay in the game for the next 10 years and longer.