Incidence of neurological complications following overstenting of the left subclavian artery

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Abstract

Objective: Aortic endovascular stent-graft implantation is associated with low morbidity and mortality rates. Overstenting of the left subclavian artery may be necessary to create a satisfactory proximal ‘landing zone’ for the stent-graft. Few cases have been published reporting adverse neurological events after overstenting of the left subclavian artery. We thus evaluated whether this procedure is associated with a higher rate of neurological complications by focusing on the management of the supra-aortic vessels. Methods: Twenty patients suffering from aortic arch aneurysms (n = 3), descending aortic aneurysms (n = 7), acute (n = 6) and chronic (n = 4) type-B aortic dissections underwent stent-graft repair with complete (n = 14) or partial (n = 6) overstenting of the left subclavian artery. Three patients underwent overstenting of the entire aortic arch with ascending aortic-bi-carotid bypass grafting. One patient with right carotid and vertebral artery occlusion underwent initial carotid-to-subclavian bypass. All patients subsequently underwent neurological examination and Doppler ultrasound for detection of neurological and peripheral vascular complications. Results: Aortic stent-graft repair was successful in all patients without acute neurologic complications. Two patients developed late central adverse neurological events: right-sided vertebral artery occlusion with brainstem infarction (n = 1) and impaired binocular vision combined with dizziness (n = 1), necessitating secondary subclavian transposition in one patient. Peripheral symptoms related to occlusion of the left subclavian artery were observed in five patients as sensory and motoric deficits of the left hand and arm. Conclusions: Overstenting of the left subclavian artery as treatment of aortic pathologies in high-risk patients is feasible but associated with the risk of neurological complications and peripheral symptoms. Side effects were mild or transient in most of our patients. Detailed preoperative exploration of vascular anatomy and pathology via Doppler ultrasound, CT- or MRI scan is mandatory to avoid adverse neurological events. Prior surgical revascularization of the left subclavian artery is essential in patients with high-grade stenoses, occlusions, or anatomic variants of the supra-aortic branches. Delayed surgical revascularization is necessary only in patients with relevant subclavian steal syndrome or severe peripheral vascular symptoms.

Keywords: Endovascular stent-graft; Supra-aortic vessels; Aortic aneurysm; Aortic dissection; Neurological complication; Subclavian artery overstenting

1. Introduction

Endovascular stent-graft implantation (ESI) is a less invasive treatment of aortic pathologies, associated with lower morbidity and mortality rates than conventional open aortic repair [1–4]. Open surgical treatment of aortic diseases necessitates aortic cross-clamping and occasionally hypothermic circulatory arrest. In contrast to open repair, ESI requires suitable proximal and distal ‘landing zones’ for stent-graft fixation. Thus, 2 cm of normal aortic wall is needed for adequate sealing [5,6]. Thoracic aortic pathologies such as aneurysms or dissections often involve the origin of the supra-aortic branches. If the distal aortic arch is affected, overstenting of the left subclavian artery (LSA) can be performed to elongate the proximal ‘landing zone’ [7,8]. However, this strategy has been associated with delayed onset of vertebrobasilary insufficiency and arm ischemia [9]. Surgical transposition of the LSA to the left common carotid artery (LCCA) or LCCA-to-LSA bypass prior to ESI is sometimes necessary to preserve the blood
flow and avoid adverse events resulting from LSA over-
stenting [10].

After preoperative evaluation of the supra-aortic vessels
we applied a tailored approach with over-stenting of the LSA
without revascularization in the absence of supra-aortic
vascular disease and performed selective subclavian revas-
cularization only in patients with supra-aortic vascular
pathology. There are a few cases reporting adverse events
after over-stenting of the LSA, and no consensus exists on how
best to manage and treat patients requiring over-stenting of
the LSA [6]. We thus evaluated whether over-stenting of
the LSA is associated with a higher rate of neurological
complications and peripheral symptoms by focusing on
management of supra-aortic vessels.

2. Materials and methods

Since 1996, we have considered ESI of aortic diseases as an
alternative to open surgical aortic repair in 265 high-risk
patients. Between December 2000 and March 2006, 20 of
these patients (10 female and 10 male) with a mean age of
64.3 ± 12.23 years (range 39—79 years) were suffering from
thoracic or thoracoabdominal aortic diseases close to or
involving the supra-aortic arteries requiring complete over-
stenting or partial covering of one or more supra-aortic
vessels with endovascular stent-grafts.

The patients’ preoperative risk factors and comorbidities
are found in Table 1. Due to the high perioperative risk these
particular patients presented, conventional surgical repair
was not deemed appropriate. Preoperative Doppler ultra-
sound of the supra-aortic branches was performed in 15
patients and was not feasible due to time constraints in five
emergent or urgent cases. In 3 of the 20 patients (15%),
preoperative Doppler ultrasound detected mild supra-aortic
vessel pathologies (wall thickening of the right and LCCA
(n = 3) and atherosclerotic plaques in the internal and
external carotid arteries (n = 2)). Two patients had severe
supra-aortic vessel pathologies with complete occlusion of
the right internal carotid and vertebral artery (n = 1) and
occlusion of the LSA based on a type-B aortic dissection with
incomplete subclavian steal syndrome (n = 1) (Table 2).

Additionally, evaluation for elective and urgent patients
was done by angiography, computed tomography (CT), or
magnetic resonance imaging (MRI) to exclude stenoses,
occlusion, or anatomical variants of the supra-aortic branches
and aortoiliac axis (Fig. 1). The supra-aortic branches were
examined to determine whether an adequate 'landing zone'
would be available.

Pathologies included aneurysms of the aortic arch (n = 3)
and descending aorta (n = 7), and acute (n = 6) and chronic
(n = 4) type-B aortic dissections. Two of the chronic dissections
involved a secondary aneurysm. Two patients (10%) had a
preoperative history of stroke and five patients had undergone
aortic surgery due to aortic type-A dissection (n = 3) and aortic
coarctation (n = 2). Seven of the 20 patients (35%) required
emergency stent-grafting for treatment of contained rupture
(n = 2) resulting from acute (n = 1) or chronic (n = 1) aortic
dissections, malperfusion of the renal and visceral arteries
(n = 3) or of the iliac and femoral arteries (n = 2). Indication for
stent-grafting in 10 patients with aneurysms (50%) was rapid
progression of aneurysm, aneurysm greater than 5 cm, or
excentric aneurysms. Ten patients with acute or chronic type-
B dissections (50%) were treated for associated complications
such as contained rupture, visceral or renal malperfusion, limb
ischaemia, persistent pain despite medication, or secondary
aneurysm associated with the dissection (Table 2).

Eleven patients with atherosclerotic aneurysms (n = 6)
and aortic type-B dissections (n = 5) in whom the LSA origin
revealed aneurysm involvement or proximity to the primary
entry site of the dissection required partial or complete
over-stenting of LSA by ESI. Nine patients in whom the
distance from the LSA to the beginning of the aneurysm
(n = 4) or to the primary dissection entry site (n = 5) was
under 1.5 cm also required partial or complete over-stenting
of the LSA (Table 3).

<p>| Table 1 Preoperative risk factors and co-morbidities |</p>
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<th>Pat</th>
<th>Stroke/TIA</th>
<th>Hypertension</th>
<th>Hyperlipidemia</th>
<th>COPD</th>
<th>Obesity</th>
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COPD, chronic obstructive pulmonary disease; CAD, coronary artery disease; TIA = transient ischemic attack.
In 14 patients, the LSA was completely overstented, preventing antegrade perfusion of the LSA. In 3 of these 14 patients, aortic-bi-carotid bypass without revascularization of the LSA was initially performed prior to overstenting of the entire aorta or carotid for aortic arch aneurysm. Simultaneous revascularization of the LSA by LCCA-to-LSA bypass was carried out in 1 of the 14 patients treated by complete overstenting of the LSA. That last patient presented with an occlusion of the right internal carotid artery and the right vertebral artery (VA) preoperatively, and a history of three strokes, ruling out any occlusion of the supra-aortic branches without additional revascularization. All initial bypass procedures were performed during the same operation prior to ESI. Details of the surgical revascularizations of the supra-aortic branches are shown in Table 3. Coverage of the LCCA with the bare metal tip of the endovascular stent-graft was necessary in four further patients in that group, which still allowed sufficient antegrade perfusion of the LCCA.

In six patients, the LSA was not completely covered by the endovascular stent-graft, thus permitting antegrade LSA perfusion. In four of those patients, the LSA was only covered by the bare metal tip, and in two of them the proximal coated portion of the stent-graft did not completely occlude the LSA orifice (Table 3).

### Table 2
Preoperative data

<table>
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<tr>
<th>Pat</th>
<th>Age</th>
<th>Sex</th>
<th>Prior cardio-vascular surgery</th>
<th>Aortic pathology</th>
<th>Supra-aortic pathology</th>
<th>Urgency</th>
<th>Rupture</th>
<th>Malperfusion</th>
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<td>Elective</td>
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<tr>
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<td>79</td>
<td>M</td>
<td>—</td>
<td>Chronic type-B dissection</td>
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<td>Urgent</td>
<td>—</td>
<td>—</td>
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<td>—</td>
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<td>Dissection involving the LSA causing proximal LSA occlusion and incomplete subclavian steal syndrome</td>
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<td>Iliac/femoral</td>
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<td>Acute type-B dissection</td>
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<td>Acute type-B dissection</td>
<td>—</td>
<td>Emergent</td>
<td>—</td>
<td>Renal/visceral</td>
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<td>39</td>
<td>F</td>
<td>Aortic coarctation</td>
<td>TAA (7.1 cm)</td>
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<td>Renal/visceral</td>
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<td>Iliac/femoral</td>
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<td>TAA (7.6 cm)</td>
<td>Plaques of the ICAs and ECAs, thickened walls of the CCAs</td>
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<td>TAA (5.3 cm) + infrarenal aortic stenosis</td>
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<td>TAA (6.0 cm)</td>
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<td>Type-A dissection, CABG</td>
<td>AAA + TAA (5.5 cm)</td>
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<td>AAA + TAA (6.0 cm)</td>
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<td>Emergent</td>
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M, male; F, female; CABG, coronary artery bypass grafting; TAA, thoracic aortic aneurysm; AAA, aortic arch aneurysm; ICA, internal carotid artery; ECA, external carotid artery; LSA, left subclavian artery; CCA, common carotid artery; VA, vertebral artery.

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In 14 patients, the LSA was completely overstented, preventing antegrade perfusion of the LSA. In 3 of these 14 patients, aortic-bi-carotid bypass without revascularization of the LSA was initially performed prior to overstenting of the entire aortic arch for aortic arch aneurysm. Simultaneous revascularization of the LSA by LCCA-to-LSA bypass was carried out in 1 of the 14 patients treated by complete overstenting of the LSA. That last patient presented with an occlusion of the right internal carotid artery and the right vertebral artery (VA) preoperatively, and a history of three strokes, ruling out any occlusion of the supra-aortic branches without additional revascularization. All initial bypass procedures were performed during the same operation prior to ESI. Details of the surgical revascularizations of the supra-aortic branches are shown in Table 3. Coverage of the LCCA with the bare metal tip of the endovascular stent-graft was necessary in four further patients in that group, which still allowed sufficient antegrade perfusion of the LCCA.

In six patients, the LSA was not completely covered by the endovascular stent-graft, thus permitting antegrade LSA perfusion. In four of those patients, the LSA was only covered by the bare metal tip, and in two of them the proximal coated portion of the stent-graft did not completely occlude the LSA orifice (Table 3).

### 2.1. Intraoperative neurophysiological monitoring

Cerebral perfusion was controlled in each patient by an arterial line placed in the right radial artery. Intraoperative neurophysiological monitoring with transcranial motor-evoked potentials (tcMEP) and somatosensory-evoked potentials (SSEP), as well as cerebrospinal fluid (CSF) pressure monitoring was applied in 17 (elective = 5, urgent = 7, emergent = 5) patients as a control mechanism to identify spinal cord ischemia during ESI (Table 3). This technique has been described in detail previously [11,12]. Whenever CSF pressure exceeded 15 mmHg, CSF drainage was carried out. In three patients who underwent emergency surgery, intraoperative neurophysiological monitoring was not applied.

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*Fig. 1. Preoperative 3D-MRI with aortic arch and thoracoabdominal aneurysm (Crawford type I) involving the supra-aortic great arteries (left); postoperative 3D-MRI after endovascular stent-graft implantation with three stent-grafts covering the entire aortic arch to the celiac axis (middle), and aortic-bi-carotid bypass using woven prosthesis (right).*
The selection of the stent-graft devices was based on availability, length, required diameter, and anatomical findings. Stent-graft diameter was calculated from the largest proximal or distal neck diameter and an over-sizing factor of 10%. The EXCLUDER/TAG (W. L. Gore & Associates, Flagstaff, AZ, USA), the Talent/Valiant (Medtronic, Santa Rosa, CA, USA), the Zenith TX 1 (Cook, Bloomington, IN, USA), and the Palmaz (Cordis Endovascular, New York, NY, USA) stent-graft devices were implanted in the operating room under general anesthesia (Table 3). For optimal visualization, the patient was positioned with the left shoulder elevated in order to maximize the distance between the supra-aortic branches’ origins. The common femoral artery access was chosen in 16 patients. Due to severe calcification, significant stenoses or occlusion of the femoral arteries, or significant thoracoabdominal kinking, an alternative stent-graft access was chosen in four patients: one common iliac artery, one infrarenal aorta, and in two cases the ascending aorta (Table 3). Intraoperative angiography was performed using ‘breath-hold’ technique using a mobile C-arm intensifier (Siemens, Munich, Germany). The stent-grafts were advanced under fluoroscopic guidance and deployed during mild systemic hypotension. We used latex balloons (Reliant balloon, Medtronic, Sunrise, FL) to improve expansion for modeling the stent-grafts to the aortic wall.

2.2. Ascending aortic-bi-carotid bypass

Following upper L-shaped hemisternotomy, the ascending aorta was exposed in usual fashion. The brachiocephalic trunk and LCCA were circumferentially dissected. After systematic heparinization with 100 IU/kg bodyweight, the ascending aorta was tangentially clamped and a longitudinal arteriotomy performed. An end-to-side anastomosis between the proximal portion of a bifurcated Dacron prosthesis (Gelseweave®, Vascutek, Scotland, UK) and the ascending aorta took place with reinforcement of Teflon felt strips with an over-sizing factor of 10%. The EXCLUDER/TAG (W. L. Gore & Associates, Flagstaff, AZ, USA), the Talent/Valiant (Medtronic, Santa Rosa, CA, USA), the Zenith TX 1 (Cook, Bloomington, IN, USA), and the Palmaz (Cordis Endovascular, New York, NY, USA) stent-graft devices were implanted in the operating room under general anesthesia (Table 3). For optimal visualization, the patient was positioned with the left shoulder elevated in order to maximize the distance between the supra-aortic branches’ origins. The common femoral artery access was chosen in 16 patients. Due to severe calcification, significant stenoses or occlusion of the femoral arteries, or significant thoracoabdominal kinking, an alternative stent-graft access was chosen in four patients: one common iliac artery, one infrarenal aorta, and in two cases the ascending aorta (Table 3). Intraoperative angiography was performed using ‘breath-hold’ technique using a mobile C-arm intensifier (Siemens, Munich, Germany). The stent-grafts were advanced under fluoroscopic guidance and deployed during mild systemic hypotension. We used latex balloons (Reliant balloon, Medtronic, Sunrise, FL) to improve expansion for modeling the stent-grafts to the aortic wall.

2.3. Endovascular stent-graft implantation

We used four types of commercial endovascular stent-graft devices in our study. The selection of the stent-graft devices was based on availability, length, required diameter, and anatomical findings. Stent-graft diameter was calculated from the largest proximal or distal neck diameter and an over-sizing factor of 10%. The EXCLUDER/TAG (W. L. Gore & Associates, Flagstaff, AZ, USA), the Talent/Valiant (Medtronic, Santa Rosa, CA, USA), the Zenith TX 1 (Cook, Bloomington, IN, USA), and the Palmaz (Cordis Endovascular, New York, NY, USA) stent-graft devices were implanted in the operating room under general anesthesia (Table 3). For optimal visualization, the patient was positioned with the left shoulder elevated in order to maximize the distance between the supra-aortic branches’ origins. The common femoral artery access was chosen in 16 patients. Due to severe calcification, significant stenoses or occlusion of the femoral arteries, or significant thoracoabdominal kinking, an alternative stent-graft access was chosen in four patients: one common iliac artery, one infrarenal aorta, and in two cases the ascending aorta (Table 3). Intraoperative angiography was performed using ‘breath-hold’ technique using a mobile C-arm intensifier (Siemens, Munich, Germany). The stent-grafts were advanced under fluoroscopic guidance and deployed during mild systemic hypotension. We used latex balloons (Reliant balloon, Medtronic, Sunrise, FL) to improve expansion for modeling the stent-grafts to the aortic wall.

2.2. Ascending aortic-bi-carotid bypass

Following upper L-shaped hemisternotomy, the ascending aorta was exposed in usual fashion. The brachiocephalic trunk and LCCA were circumferentially dissected. After systematic heparinization with 100 IU/kg bodyweight, the ascending aorta was tangentially clamped and a longitudinal arteriotomy performed. An end-to-side anastomosis between the proximal portion of a bifurcated Dacron prosthesis (Gelseweave®, Vascutek, Scotland, UK) and the ascending aorta took place with reinforcement of Teflon felt strips with an over-sizing factor of 10%. The EXCLUDER/TAG (W. L. Gore & Associates, Flagstaff, AZ, USA), the Talent/Valiant (Medtronic, Santa Rosa, CA, USA), the Zenith TX 1 (Cook, Bloomington, IN, USA), and the Palmaz (Cordis Endovascular, New York, NY, USA) stent-graft devices were implanted in the operating room under general anesthesia (Table 3). For optimal visualization, the patient was positioned with the left shoulder elevated in order to maximize the distance between the supra-aortic branches’ origins. The common femoral artery access was chosen in 16 patients. Due to severe calcification, significant stenoses or occlusion of the femoral arteries, or significant thoracoabdominal kinking, an alternative stent-graft access was chosen in four patients: one common iliac artery, one infrarenal aorta, and in two cases the ascending aorta (Table 3). Intraoperative angiography was performed using ‘breath-hold’ technique using a mobile C-arm intensifier (Siemens, Munich, Germany). The stent-grafts were advanced under fluoroscopic guidance and deployed during mild systemic hypotension. We used latex balloons (Reliant balloon, Medtronic, Sunrise, FL) to improve expansion for modeling the stent-grafts to the aortic wall.

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Aortography documented adequate aneurysm exclusion, sealing of the proximal entries in cases of aortic dissection, and occurrence of endoleaks. We defined successful ESI as deployment in the correct aortic passage with satisfactory blood flow proximal and distal of the stent-graft.

2.4. Follow-up

Follow-up CT- or MRI scans were performed before hospital discharge and after 3, 6, and 12 months, and annually thereafter (Fig. 1). Mean follow-up was 19.7 ± 17.3 months (range 2–60 months). All pre- and postoperative clinical examinations, as well as those during follow-up included bilateral blood pressure measurements, multislice CT- or MRI scans, and Doppler ultrasound of the supra-aortic vessels.

2.5. Neurological evaluation and examination

All surviving 18 patients underwent neurological follow-up performed by an experienced neurologist. A careful medical history was taken to detect transient or persistent neurological deficits prior to or after ESI. Furthermore, we took thorough patient histories, enquiring in particular about transient or persistent central neurological deficits (i.e., brainstem ischemia becoming manifest in vertigo, dizziness, acute deficits in motoric function or sensibility, dysarthria, dysphagia, or ocular movement disorders) or peripheral symptoms (i.e., arm claudication, numbness, or weakness) at rest or following exercise of the ipsilateral upper limb.

Neurological examination was performed to detect cranial nerve lesions with special attention paid to the existence of left-sided Horner syndrome. Furthermore, the motor-sensory system was examined with special regard to central or peripheral origin of paresis or sensory disorders of the left upper extremity, and to cerebellar or gait disorders. Subclavian steal syndrome was defined as presence of subclavian steal effect as diagnosed by ultrasound and the presence of clinical symptoms [13].

2.6. Ultrasound examination

Ultrasound measurements were taken by two experienced sonographers assessing the carotid arteries using Doppler ultrasound scanning. A 2 MHz probe was used for transnuchal scanning of the vertebrobasilar vascular territory; 4 MHz linear and 8 MHz curved array scanners were employed for examination of extracranial arteries (HDI 5000: ATL Bothell, USA). With the patient in a supine position, a careful search was made for transverse and sagittal planes of all supra-aortic vessels (i.e., the proximal and distal subclavian artery, the VAs from the origin to intracranial course including the basilar artery, and the common, external, and internal carotid arteries on both sides). Associated graft interponents (e.g., aortic-bi-carotid bypass) were carefully analyzed for superimposed thrombi or stenoses defined as circumscribed luminal narrowing in B-mode and significant flow acceleration in Doppler ultrasound.

We classified the degree of subclavian steal effect (i.e., the extend of hemodynamic changes in the vertebral arteries in ultrasound measurement regardless of clinical symptoms), varying from (I): systolic flow deceleration, to (II): alternating flow profile, to (III): completely reversed flow. LSA occlusion or high-grade stenoses were assumed in cases of completely reversed flow in the ipsilateral VA and upon detection of vertebro-vertebral, carotido-vertebral, or externo-vertebral collateral flow. Diagnosis of subclavian steal effect was confirmed using functional tests based on reactive hyperemia following compression of the upper left extremity, which resulted in an increase in the reverse component of the VA blood flow. Furthermore, a difference in blood pressure in the radial arteries or a difference in blood pressure between both arms ≥ 30 mmHg confirmed the diagnosis.

2.7. Data collection

In accordance with current legislative recommendations, all interventions were performed with approval of our institutional review board. All patients were informed in detail about ESI and additional revascularization procedures. All patients provided written consent. Data were maintained in a database of this Department of Cardiovascular Surgery. The collected data were reviewed according to the guidelines indicated by our institutional review board.

3. Results

Aortic stent-graft repair was successful in each patient in this series. All aneurysms were excluded without intraoperative complications. Closure of the entry tear and expansion of the true lumen with reperfusion of visceral, renal, or iliac arteries was achieved in all patients suffering from chronic or acute aortic dissections. The mean number of stent-grafts in all 20 patients was 1.65 (range 1–4) with a mean overstented aortic portion of 22 cm in length. Mean duration of all procedures was 189 min (30–550 min). The median hospital stay was 12 days.

3.1. Intraoperative neurophysiological monitoring

No patient suffered from complications related to spinal cord ischemia, even though we observed alterations in tcMEP (i.e., extended latency or shortened amplitude) in three cases after stent-graft deployment. When alterations of evoked potentials occurred, we initiated spinal-cord protection efforts. These protection methods have been described in detail [11,12]. In all other 14 patients measured, tcMEP potentials were consistent at the end of the operation. SSEP potentials were consistent in all measured patients.

3.2. Follow-up

Our follow-up was 100%. Two patients in our series died of unrelated causes, yielding no mortality related to ESI. One developed necrotic pancreatitis with peritonitis resulting in multiorgan failure 72 days after the ESI procedure. In that case, the LSA had only been covered with the bare metal tip of the stent-graft device, allowing antegrade perfusion of the LSA. The other patient had a complete overstented LSA and died 3 years after the initial operation.
3.3. Hemodynamics and peripheral symptoms related to LSA occlusion

Occlusion of the LSA was followed by a differential in blood pressure between the right and the left arm. A lower \((n = 5)\) or complete loss \((n = 5)\) of blood pressure of the left arm occurred postoperatively in 50% of the patients. During follow-up, four patients with completely overstented LSA still had left arm pulses that could be measured noninvasively.

Pathological blood flows in the supra-aortic branches were detected in 10 of the 14 patients \((71\%)\) who had undergone complete LSA occlusion. Doppler ultrasound showed development of subclavian \((n = 2)\), vertebro-vertebral \((n = 2)\), vertebro-basilar \((n = 2)\), combined vertebro-vertebral, and carotid-vertebral \((n = 2)\) steal effects, as well as crossflow in the deep neck arteries \((n = 1)\). The following degrees of subclavian steal effects (SSE) were observed: (I) systolic deceleration \((n = 1)\); (II) alternating flow profile \((n = 2)\); and (III) completely reversed flow \((n = 7)\). The relationship between flow patterns and vascular peripheral symptoms is shown in detail in Table 4. Of the 14 patients with complete overstenting of the LSA, 5 patients \((36\%)\), developed associated peripheral symptoms. All had pathological blood flow degree III. These five patients suffered from ischemic-related peripheral arm deficits such as exercise-induced, sensory \((n = 3)\), and motoric \((n = 3)\) deficits of the left hand, temporary \((n = 1)\) and persisting \((n = 2)\) weakness of the left arm, and sensory deficits (numbness) of the left arm \((n = 3)\). The symptoms were mild and improved over time in four of them, not necessitating subclavian revascularization. One of them presented 4 months after the initial operation with a combination of several neurological symptoms such as numbness of the left arm and hand, weakness of the left arm, and disturbed fine motor skills of the left hand. The patient was successfully treated surgically with delayed LCCA-to-LSA bypass and proximal LSA ligation leading to improvement of symptoms. In the remaining five patients with pathological blood flow \((I = 1, II = 2, III = 2)\), no peripheral symptoms were observed (Table 4).

In the group of patients \((n = 6)\) in whom complete overstenting of the LSA was avoidable, we identified no pathological changes in supra-aortic blood flow.

3.4. Neurological outcome

All patients recovered from surgery without any initial signs of significant neurological complications during their hospital stay. In the follow-up period, none of the 14 patients with complete overstenting of the LSA developed reversible...
exercise-induced signs of central vertebrobasilar insufficiency, including the 10 patients who had a subclavian steal effect detected on Doppler examination. Five of 20 patients (25%) presented with adverse neurological events during follow-up (Table 4). In two (10%) of them, neurological events were associated with complete LSA occlusion. These two patients suffered from late central neurological events such as right-sided brainstem infarction \((n = 1)\) and transient ischemic attack manifested by impaired binocular vision combined with dizziness \((n = 1)\). The acute right-sided pontine brainstem infarction, confirmed by cerebral MRI, occurred 2 months after ESI due to an acute occlusion of the right hypoplastic VA causing left-sided facial paresis, dysarthria, severe hemiparesis, and hemihyposthesia (initial NIH stroke scale = 14). The patient underwent LSA transposition to the LCCA to prevent further brainstem infarction due to the impaired perfusion of the vertebro-basilar arteries.

Other neurological complications not related to the occlusion of supra-aortic vessels occurred in three patients. One suffered from dysesthesia due to a lesion of a cutaneous branch of the right femoral nerve (stent-graft access), another patient was hoarse as a result of recurrent laryngeal nerve irritation following aortic-bi-carotid bypass, and the third patient suffered from intracerebral bleeding unrelated to previous surgery due to a hypertensive crisis while under anticoagulation therapy (Table 4).

3.5. Endoleaks and other stent-graft related problems

We identified postoperative problems with the implanted stent-grafts via CT scans during follow-up. No type II endoleak due to over-stenting of the LSA was observed in our cohort. In one patient (5%), an incomplete seal in the proximal attachment zone (type Ia endoleak) occurred, and two patients (10%) showed an incomplete seal between the stent-graft segments (type III endoleak). All three patients were successfully treated with additional stent-grafts, in a mean time of 133 days (range 10–400 days). The initial implanted stent-graft in another patient collapsed 1 year after implantation due to material failure. This patient was also successfully treated with an additional stent-graft.

4. Discussion

Open surgical repair of the aortic arch, the descending and the thoracoabdominal aorta are invasive procedures with high morbidity and mortality rates \([4,14]\). ESI is a less invasive and effective treatment for high-risk patients showing a low complication rate \([11,12]\). One of the most difficult aspects of stent-graft application is the absence of an adequate proximal ‘landing zone’, because the LSA is often involved in or too close to aortic pathologies.

For optimal stent-graft fixation, the ‘landing zones’ should be over 2 cm long. Patients with a proximal ‘landing zone’ of at least 1.5 cm can undergo ESI with the intention to preserve antegrade flow in the LSA. Complete coverage of the LSA ostium must take place occasionally to expand the application of stent-graft devices for aortic pathologies beside the LSA \([15]\). The carotid arteries limit the use of stent-grafts in pathologies located in the aortic arch.

Patients with atherosclerotic subclavian artery stenoses or occlusions are often asymptomatic, as the slow disease progression promotes collateral vessel development \([16]\). The LSA is not usually transposed, because LSA over-stenting without revascularization is a well-tolerated procedure in patients with normal supra-aortic branches \([17,18]\). In contrast, acute LSA occlusion by over-stenting of the LSA in the absence of collateral vessels might lead to problems induced by ischemia.

In the study of Görich et al. \([17]\) of incomplete LSA over-stenting in 4 and complete occlusion of the LSA in 19 patients, three patients (13.6%) reported ischemic arm symptoms but none of them showed persistent signs of vertebrobasilar insufficiency. In the series of Tiesenhausen et al. \([9]\), three of eight patients (37.5%) with partial or complete occlusion of LSA had vertebrobasilar symptoms. In the study of Schoder et al. \([2]\), six of eight patients (75%) with complete occlusion of the LSA presented symptoms. Secondary transposition of LSA was necessary in two of those patients, in one patient to treat critical arm ischemia and in the other to treat an endoleak. Paraparesis and paraplegia occurred in 5.1% of their patients. One of them underwent over-stenting of the LSA.

Surgical revascularization of the supra-aortic vessels may present a potential strategy for expanding the applicability of thoracic aortic ESI. Some patients require revascularization of the LSA, such as CABG patients with patent left internal mammary arteries, because LSA occlusion in such cases may cause myocardial ischemia \([19]\). Anatomic variants, such as origin of the left VA at the arch, or the absence of fusion of the VAs to the basilar artery, or an otherwise functionally-compromised circle of Willis, do not permit LSA occlusion without previous revascularization \([2]\). As reported in the literature, occlusion of one VA caused vertebrobasilar ischemia resulting in cerebellar infarction in 2.7% \([20]\). Bilateral VA occlusion (by over-stenting of the LSA and an additional pathological right VA) caused persistent neurological deficits in 23% of the patients \([2]\). Carotid or vertebral artery stenosis as well as aberrant subclavian arteries (lusoria) require revascularization of the LSA, as over-stentening of the lusorian artery carries the increased risk of consecutive cerebellar infarction \([15,19]\).

Another indication for transposing the LSA, or for LCCA-to-LSA bypass surgery with proximal ligation, is to avoid retrograde perfusion of the aneurysm sac or the false lumen in dissections \([9]\). With coverage of the LSA, retrograde perfusion from the LSA may prevent thrombosis in the aneurysmal sac and can cause type-II endoleaks. Interestingly, we observed no type-II endoleaks after complete over-stenting of the LSA in our series. If type-II endoleaks occur, coil embolization or surgical ligation of the LSA may become necessary \([14]\). The rate of primary endoleaks after thoracic aortic ESI was reported to be 11–25% \([2,7,10]\).

In case of aortic arch involvement, other surgical revascularization techniques to maintain cerebral perfusion have been developed to make ESI in the aortic arch possible \([21–23]\). Czerny et al. \([24]\) carried out reconstructions of the supra-aortic branches in patients with aortic arch aneurysms or type-B aortic dissections. Treatment was by sequential transposition of the LCCA into the brachiocephalic trunk and of the LSA into the already-transposed LCCA.
However, surgical revascularization of the LSA has a 1–5% mortality rate [15]. Surgical complications after LSA transposition in Schoder et al.'s [2] series were Horner syndrome and hoarseness in 7.1% of the patients. An 11% rate of recurrent nerve paralysis was described in another series [6]. Therefore, we question the need for prophylactic LSA transposition or LCCA-to-LSA bypass due to the fact that most patients with subclavian steal syndrome are asymptomatic. Flow inversion from a normal right VA to the left VA seems adequate to compensate after LSA occlusion in patients with normal supra-aortic vessels. These revascularization techniques should thus be reserved only for those patients developing ischemic symptoms or presenting a potentially compromised collateral blood supply.

To summarize, our results clearly demonstrate the difficulty and complexity of endovascular stent-graft repair of the aortic arch and extending aortic pathologies with overstretching of the supra-aortic branches. In the absence of supra-aortic vascular pathologies, intentional LSA occlusion may be justified when a proximal 'landing zone' for ESI is required without subclavian revascularization. Hemodynamically relevant stenoses, occlusions, or anatomic variants of the supra-aortic branches are preoperative risk factors that can lead to a higher rate of neurological complications after LSA overstretching. Preoperative exploration of the supra-aortic branches by Doppler ultrasound, CT- or MRI scan is therefore mandatory. Surgical supra-aortic revascularization techniques managing aortic arch vessels can expand the applicability of ESI even in patients presenting with stenoses, occlusions, or anatomical variants of the supra-aortic branches. Should overstretching of the LSA become necessary in patients with insufficient collateral pathways and a thus significantly increased risk of brain ischemia or peripheral ischemic events, we recommend revascularization of the supra-aortic branches in advance rather than as a secondary procedure. In the absence of supra-aortic vessel pathologies, prophylactic transposition of the LSA or LCCA-to-LSA bypass is not required prior to intentional stent-graft occlusion of the LSA, but surgical revascularizations may be designated as an elective measure after ESI when ischemic symptoms do occur.

In conclusion, overstretching of the LSA resulted in ischemic disorders and neurological events in a number of our patients. However, coverage of the LSA and other supra-aortic vessels — to make ESI possible in the aortic arch and in the presence of descending aortic pathologies with additional supra-aortic revascularization — is an effective treatment for high-risk patients with an overall lower rate of morbidity and mortality compared to open surgery.

References

Dr M. Turina (Zurich, Switzerland): Thank you very much for this report, which raises many questions really. Would you consider monitoring the blood pressure in the left radial artery as sufficient during over-stenting or do you rely simultaneously on the ultrasound measurements in the operating room?

Dr Weigang: We monitored the blood pressure on both arms pre-, intra- and postoperatively. Surprisingly, we found a blood pressure signal on the left arm as well in some of our patients undergoing over-stenting of the left subclavian artery. We do not take ultrasound measurements during these procedures.

Dr G. Ziemer (Tuebingen, Germany): When you checked your supra-aortic flow after implantation of the graft you said you had two subclavian steal syndromes but you didn’t treat them. So I think you did not mean subclavian steal syndrome as this would imply neurologic symptoms. You meant just flow reversal in the vertebral artery without symptoms, which is not subclavian steal syndrome. So was there reverse of the flow in the left vertebral artery without symptoms?

Dr Weigang: Yes, that’s right. Most of these patients had no severe neurological symptoms.

An independent neurologist performed the follow-up examinations of our patients after the over-stenting of the left subclavian artery. He observed two subclavian steal syndromes and other collateral pathways such as vertebro-vertebral, vertebro-basilar, combined vertebro-vertebral, and carotid-vertebral steal effects as well as crossflow in the deep neck arteries.

Dr Turina: The comment is totally right, because speaking of a syndrome denotes symptomatic or subclavian reduction or reversal of the flow. The title of your slide is correct but the terminology is not.

Dr Weigang: Some of the patients had subclavian steal syndrome.

Dr Ziemer: Flow reversal in the left vertebral artery, which does not lead to symptoms and therefore it is not a syndrome. This should be easily distinguished.

Dr Weigang: But they had symptoms, as I showed here.

In the group with complete over-stenting of the left subclavian artery we observed two central neurological complications. One patient had brainstem infarction with hemiparesis and the other patient suffered from impaired vision and dizziness due to transient ischemic attack.

Additionally we observed peripheral symptoms in five patients in the same group, including numbness of the left arm or hand, disturbed fine motor skills of the left hand, weakness of the left arm due to arm claudication.

Dr Ziemer: Then the syndromes, namely symptomatic patients have to be in the clinical findings list or slide.

Dr Weigang: They had symptoms. Five of our patients had peripheral and two had central neurological symptoms. Another three patients presented with neurological symptoms which were not related to over-stenting of the left subclavian artery.

Dr Ziemer: Semantics possibly. Vertebral artery flow reversal without symptoms is no syndrome.

Dr Weigang: That is a question of definition.

Dr Turina: So you mean eight of the 14 had symptoms and that had a subclavian steal syndrome?

Dr Weigang: Yes.

Dr Turina: Six did not.

Dr P. Ghosn (Montreal, Canada): I have two questions. The first one is how do you explain the right-sided infarction in your series? And the second one, in view of the high percentage of symptoms after the subclavian exclusion, did you consider doing a bypass to the subclavian artery prior to putting your stent graft into the aorta?

Dr Weigang: To answer your first question, this was a patient who suffered from a right-sided brainstem infarction two months after the initial operation. At that time that patient had developed a new occlusion of the right vertebral artery. To prevent another brainstem infarction we performed a left subclavian transposition in him.

Can you repeat your second comment, please?

Dr Ghosn: About bypassing the left subclavian artery before inserting your stent graft, like a carotid subclavian bypass or carotid subclavian transposition to keep the flow going into the subclavian artery before inserting your stent graft in the aorta.

Dr Turina: The question is why don’t you consider putting the graft first and then over-stenting.

Dr Weigang: The literature describes many complications with such revascularization techniques. The mortality rate is 1–5% for subclavian transposition and bypass grafting of the supra-aortic branches. Therefore, we carry out these examinations in advance of the stent-graft implantation. If a proximal landing zone with over-stenting of the left subclavian artery is necessary, we perform subclavian transposition or carotid-to-subclavian bypass only when anatomic variants, stenoses or occlusion of the supra-aortic branches have been detected in the preoperative examinations.

Dr Turina: And blood pressure reduction in the radial artery would not be considered an indication?

Dr Weigang: No. We had patients with no blood pressure signal in the left arm without symptoms. On the other hand, we had patients with complete over-stenting of the left subclavian artery with neurological symptoms and a blood pressure signal around 70 mmHg in the left arm.

Dr M. Krasoł (Zabrze, Poland): I would like to ask you one question regarding your antihypertensive regimen postoperatively, because if you have to rely on collateral flow that is reversible in vertebral artery flow, you would expect to have some higher pressure, because it is not regular flow, and having that, probably some deficits could not happen. This is one remark.

And second, we have had several patients with complete over-stenting of the left subclavian artery, and in these patients there was no pulsatile flow at the left radial artery. And probably, in my opinion, if you have pulsatile flow and pressure as high as 70 mmHg, it is not complete covering.

Dr Weigang: To address your second question first: after the procedure, we routinely perform CT scans in all of our patients. Fourteen of our patients underwent complete covering of the left subclavian artery without type-II endoleaks.

And regarding your first remark: if you have good intracranial cross flow and collateral flow, the patients don’t have such symptoms. However, neurological complications after endovascular stent-graft repair in the aortic arch and the descending aortic position are underreported in the literature, because most of these problems do not occur until after a couple of months. And I am quite sure that if you are sending your own patients to an independent neurologist, they will find also some of the problems you never expected.

Dr Krasoł: What was the mean age of the group with left subclavian artery over-stented, because it is also an issue? If you have pretty young patients you have a safer approach, if you have older patients, the risk is much higher. The mean age in the group?

Dr Weigang: The mean age of our patients with over-stenting of the left subclavian artery was 64 years.