Table 1 Characteristics of Patients With a Blunt Aortic Injury Treated With Stent-Grafting

Case	Age (yr)	Gender	Cause of BAI	Time (h)*	ISS	RTS	PS (%)	Fenestrated SG	LSA Preserved	Proximal Zone	Diameter of Aorta† (mm)	Diameter of SG (mm)
1	49	Male	Fall	60	29 (C4, A2, E3)	6.376	90.8	No	No	Zone 2	24	28
2	73	Femal	Traffic accident	66	25 (C4, E3)	6.376	70.6	Yes	Yes	Zone 1	29	32
3	57	Male	Fall	3	29 (H3, C4, E2)	7.841	84.9	Yes	No	Zone 0	29	30
4	77	Male	Traffic accident	3	41 (H5, C4)	3.565	6.1	Yes	Yes	Zone 1	34	36
5	30	Female	Traffic accident	8	66 (H5, C5, E4)	5.967	24.3	Yes	Yes	Zone 2	20	24
6	74	Female	Traffic accident	6	36 (H4, C4, A2)	6.171	44.8	No	NA	Zone Th4	31	34
7	83	Female	Traffic accident	8	36 (H4, C4, E2)	5.439	31.0	No	NA	Zone Th4	29	30
8	51	Male	Fall	3	29 (C4, A2, E3)	7,841	97.0	No	NA	Zone Th7	29	32
9	36	Male	Traffic accident	5	36 (H4, C4, A2)	5.235	68.5	No	No	Zone 2	28	30
10	37	Male	Jet ski accident	26	25 (C4, E3)	6.376	93.2	Yes	Yes	Zone 2	25	28
11	48	Male	Traffic accident	28	25 (H3, C4)	7.108	96.1	Yes	No	Zone 0	29	30
12	41	Male	Fall	3	29 (C4, A2, E3)	7.108	94.7	Yes	Yes	Zone 2	27	30
13	66	Female	Traffic accident	4	29 (F2, C4, E3)	7.108	81.8	Yes	Yes	Zone 1	27	32
Mean	55.5 ± 17.5	8 male (61.5%)		17.2 ± 22.0	33.5 ± 11.0	6.347 ± 1.161	68.0 ± 31.1	8/13 (61.5%)	6/10 (60.0%)		27.8 ± 3.4	30.5 ± 3.0

* Indicates the time from onset to stent-grafting.
† Indicates the aorta as a proximal landing zone.
ISS, injury severity score; RTS, revised trauma score; PS, probability of survival; SG, stentgraft; NA, not appricable.

Fig. 2. *Distribution of stent-graft placement locations in 13 patients with* BAI. *See text for a detailed description of the placement zones. Values are numbers (%) of patients. No stent-grafts were placed in zone 3.*

Fig. 3. CT *and* DSA *images obtained from a patient who underwent stent-graft treatment of aortic trauma. Preoperative and postoperative* CT *images (*left*) show, respectively, a massive mediastinal hematoma and complete resolution of the hematoma. Preoperative and postoperative* DSA *images (*right*) show, respectively, the aortic injury (*white arrowheads*) and complete exclusion of the pseudoaneurysm resulting from the injury. In this case, the* LSA *was simply covered with a stent-graft, whereas the brachiocephalic (*BCA*) and* LCCA *were well preserved by placement of a fenestrated stent-graft. The* LSA *was seen by retrograde blood flow.*

was development of a type Ia endoleak 7 months postoperatively in a 36-year-old patient in whom a nonfenestrated stent-graft was placed from zone 2 to simply cover the LSA. Complete exclusion of the aortic isthmus pseudoaneurysm was observed on postoperative CT images, but adequate conformation of the stent-graft to the inner curvature of the native aortic arch was not achieved. The patient underwent successful open repair and discharged home. However, the patient died of massive hemoptysis in his home. Exact reason of his sudden death was unclear because autopsy was not allowed. Any other death or events have not been observed during the follow-up periods.

DISCUSSION

An increasing number of cases of BAI are being treated with TEVAR.[2,9] The early and mid-term results of this procedure are better than those of conventional open repair,[3] but its long-term results remain unknown and some problems specifically associated with TEVAR for BAI have been recognized. For example, because most BAIs, reportedly more than 90%,[10] occur at the aortic isthmus, endovascular exclusion of the pseudoaneurysm is highly challenging. This challenge may be further enhanced by the presence of an acutely angulated distal aortic arch,[4] which is more likely to be present in young patients.

BAI-specific TEVAR issues have generally been addressed in one of two different ways. Previously, some authors reported that the abdominal aortic components of endografts (main-body extension cuffs) are suitable for BAI repairs in patients with an aortic diameter of less than 23 mm or a small distal arch curvature radius.[7] However, although the use of multiple short extension cuffs may improve conformation to the distal arch curvature, the procedure has some possible risks,[11] including component separation and type III endoleaks. According to the 2007 American Association for the Surgery of Trauma report,[2] the relatively high rate (20%) of repair site complications after TEVAR for BAI may have resulted from use of the abdominal aortic cuff technique in early repairs. Currently, this method is not commonly employed because of the availability of commercially manufactured thoracic aortic endografts.

A more recently developed technique is extension of the proximal landing zone toward the LCCA, without reconstruction of the LSA, by using commercial thoracic aortic endografts.[5,6] The goal of this procedure is to provide a proximal landing zone that is long enough to prevent type Ia endoleaks. However, simple coverage of the LSA is not always safe because the vertebral artery, as a branch of the LSA, sometimes has a critical role in the circulation to the posterior cerebral lobe, brain stem, cerebellum, and spine.[12] Previously, we found that 2 of 31 patients (6.5%) were adversely affected by an LSA balloon occlusion test.[13] One patient lost consciousness after several seconds after LSA balloon occlusion, whereas the other had vertigo after several minutes after LSA balloon occlusion. Although a 6.5% rate of adverse effects might be considered negligible in the context of the emergency situation characteristic of BAI, preservation of the LSA is clearly preferable in all patients. Although we have no experience of transcranial Doppler[14] to decide whether or not antegrade blood flow into the LSA is mandatory for the patients whose LSA has to be covered during TEVAR, the evaluation using transcranial Doppler might be helpful.

We think that a long, straight proximal landing zone is the key to successful endovascular exclusion of pseudoaneurysms resulting from BAI (Fig. 4). Moreover, even an acutely angulated distal aortic arch has a relatively straight segment. In the current series, we found that use of a fenestrated stent-graft allowed the aortic arch to be used as the proximal landing zone, with preservation of the BCA and the LCCA. Regarding a case of 36-year-old man who required open repair 7 months after TEVAR, an acutely angulated distal aortic arch of the patient was not appropriately assessed due to unavailability of preoperative 3D-CT images. Nonfenestrated stent-grafts (Gore TAG Thoracic Endoprosthesis, WL Gore & Associates, Flagstaff, AZ) were used in the 140-patient series of Bavaria et al.,[16] who observed an endoleak rate of 11% in patients in whom the devices were placed distal of zone 2 even though most subjects of the study consisted of atherosclerotic pathology which is supposed to have less-acutely angulated distal aortic arch. Therefore, a reduction in endoleaks may require extending the proximal landing zone more proximally from the LCCA. In patients with BAI, whose conditions are critical, it may be preferable to accomplish this goal by using a fenestrated stent-graft, without concomitant procedures such as head vessel debranching.

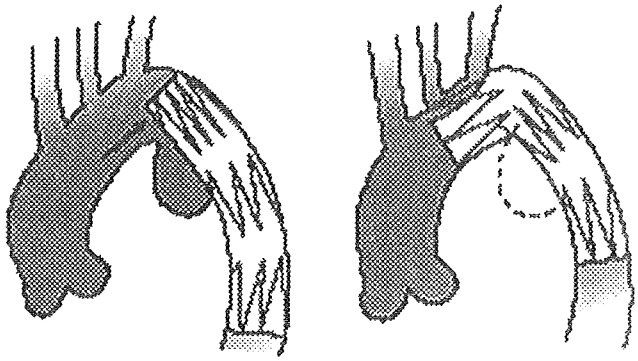

Fig. 4. *Two possible placements of a stent-graft for* BAI. *If the stent-graft is placed just distal of the* LSA (left), *there is a risk of endoleak and graft collapse because of a lack of conformation to the aortic arch* (arrow). *If the stent-graft is placed proximal of the* LSA (right), *complete exclusion of a pseudoaneurysm can be expected. Referred with permission from* Circulation Up-to-Date. *2008; 377–383.*

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DISCUSSION

Dr. Aurelio Rodriguez (Pittsburgh, Pennsylvania): In order to place in perspective my two questions, allow me to in tone with the political times, my initial comments will be on experience, change. And I promise not to talk about the "bridge to nowhere" or lipsticks.

Experience. I have no experience placing an endovascular stent. As a matter of fact, I never have seen one. However, I have been personally involved in the repair of hundreds of traumatic ruptured aortas in my 22 years in Shock Trauma in Baltimore, MD.

I did it, not because I was good, but because the cardiac surgeons in those days were not interested in repairing the aorta. They were doing $50,000 a day. They weren't interested in an aorta.

I have suffering moments and glory moments, so I can say that a stent is a gift; it came from heaven. It is a gift from heaven, really, the stents.

The endovascular stents at the beginning, as you know, they were placed. Every day they were placed in three cases here, four cases in this hospital and the other hospital.

They were removed because they were not approved. They came back. And, yes, maybe there were occlusions of the subclavian artery. Nobody talked very much about that.

So recently, the developments or the colleague from Japan have demonstrated, that a stent is unique. And I think it will be continually evolving. Hopefully, in the future the stents will replace almost all the repairs of traumatic ruptured aortas.

I have two questions. In the United States of America the stents are placed in the majority, it is my understanding by the vascular surgeons. I call it the SSS, the Secret Society of Stent.

Why do I call that? I called my vascular surgeon who puts in the stents in my hospital. He refused to talk to me. I called the hospital surgeon who put in all the stents across the river in the big university – your university.

He yelled at me and he screamed. He didn't want to give me information about it, so there is a lot of secrecy in this stent. They all claim that they publish this in some obscure journal. I never found it. Okay?

So who does the stents in Japan? The vascular surgeons? The trauma surgeons? Like our President, who went to a special course? Certainly, my hospital would not allow me to put in stents, even if I were to take a course. Okay? Who does the stents in your hospital?

And the second question is, in the land of Japan, in the land of gadgets, like Japan is, what percentage of traumatic ruptured aortas are there that do not have open repair? And what percentage are done with the stents?

The study, though, the review by Dr. Demetriades and in only 24 trauma centers, he said that 65 percent of the United States are done these days by stents.

Maybe it's true. I hope it's true. So what happens in Japan? Thank you very much for the privilege. Bail me out.

Dr. L.D. Britt (Norfolk, Virginia): I must submit that I'm violating one of the rules that I have put on myself as Program Chair never to comment during the scientific meeting and to allow the members to comment.

But I would be remiss if I did not highlight this. Is there a cohort of patients that benefit from inter-vascular stent? Yes. Is there a standard of care today? No. I want to sprinkle some caution.

We still cannot really embrace the compliance problem. Once you put in the stent you must follow these patients for life. And it's tough following trauma patients for life, Number 1.

Number 2, no one knows the durability of these grafts. You put it in a young person and they might fray in 10 or 15 years. And should they fray and you have to replace it, it's no sort of "walk in the park" to take these out and replace them.

Number 3, having just presided over the Hallstead Society as President, there was a great paper presented where they're beginning to see paraplegia in the vascular stents.

And then my last comment – and I promise I won't say any more the rest of the meeting – but the vascular surgeons, as my colleague has said, are doing most of these now because they do catheter-based management.

The cardio-vascular surgeons are walking away from even addressing this problem, which I think is a problem of

biblical proportion. And I promise not to say any more so I would love for my colleague to respond to this.

Dr. Yoshihko Kurimoto (Sapporo, Japan): Thank you for questions. In Japan, aortic endovascular stent-grafting is generally performed by a vascular surgeon.

I have a history, a ten-year history of vascular surgery and now I'm working in the emergency department. So I take care of aortic emergency stent grafting in our hospital.

In Japan, unfortunately we have no commercially-available stent graft device, so probably I think that less than 10 percent with blunt aortic injury are treated by endovascular therapy.

But I think Japanese physicians also follow the United States' experience. And I definitely agree that long-term follow-up will be necessary for patients who underwent endovascular therapy. Considering a long follow-up period and unknown late complications, we have not performed stent-grafting for young patients, except for in an extraordinary situation.

Saving lives is our priority. And not only to save the life, but also, we want to provide a better quality of life for patients with blunt aortic injuries. So I believe this less-invasive treatment is preferable for trauma patient with blunt aortic injury.

And regarding paraplegia according to the many records of endovascular therapy, paraplegia rate is much less in endovascular therapy group so open repair is less useful in terms of postoperative paraplegia. Thank you.

EDITORIAL COMMENT

Endovascular management (TEVAR) of traumatic rupture of the descending thoracic aorta (TRA) seems to have greater and greater acceptance compared with open repair, in some instances as a temporizing measure.[1] Part of the reason is that there is a perception that TEVAR is associated with a reduction in mortality (particularly in more critically injured patients) and neurologic injury.[2]

Apart from the concerns regarding lack of significant follow-up data, the issues regarding risks of TEVAR are based on the vagaries of a 2–4 cm stretch of aorta, from the origin of the left common carotid to just distal to the origin of the left subclavian artery. Issues regarding diameter, degree of angulation, ability to get apposition against the inner curve, "anomalous" origin of the vertebral artery from the arch, and risk of posterior stroke occasioned by subclavian occlusion interfering with vertebral flow all have an impact on when to use TEVAR, what type of device to use, and where to land it.[3] Added to this are differences at the extremes of age, with hyperdynamic but fragile aortas in younger patients as opposed to stiffer, but more atheromatous, vessels in older patients. The risk of stroke with TEVAR is related to the degree to which posterior cerebral circulation is dependant on left vertebral perfusion and the risk of emboli or injury occasioned by wire or device manipulation in the arch of the aorta. Late stroke may occur because of embolism, particularly in settings when the origin of a great vessel is partially crossed, but this is a theoretical risk because the incidence of this has yet to be properly documented. In the majority of younger patients, the risk of stroke is $<1\%$ and so if confronted with an immediate need to use TEVAR, and if the origin of the left subclavian must be covered then this should be done.[2] If it is felt that left subclavian perfusion must be maintained (because of a patent mammary graft or risk of stroke), then options include carotid-subclavian bypass or transposition, or "kissing" stents placed via a brachial access.

A dreaded complication of TEVAR, particularly in younger patients with trauma, is acute or delayed endograft collapse and/or intimal tear leading to type A dissection or free perforation.[4] The risks of these occurring are linked to a combination of factors and include relative over sizing of the device, vigorous ballooning, and/or lack of apposition along the inner curvature. A number of approaches have been used to reduce the risk of these complications, including using smaller diameter and shorter "stacked" abdominal components, developing curved devices, and/or using proximal bare extensions to improve inner curve apposition. Using bare metal proximal components in younger patients does raise the concern of creating injury, although it has been used to treat stent collapse.

This preamble is necessary when considering the article by Kurimoto and colleagues. The authors use anatomic-specific, precurved, and shaped devices that they can prepare in a relatively quick time frame. A requirement is that the patient be completely stable. Their goal is to show that a device can be made that can take into account the vagaries of the distal arch and proximal descending aorta. They do use some bare extensions to help the device conform to the aortic curvature. In addition, they describe a clinical test to determine the relative risk of interfering with left vertebral perfusion. Thus, assuming one agrees that in this subset of patients a TEVAR approach is better than open repair, the authors have expanded the horizon of device-specific changes that may increase the utility of TEVAR by addressing the anatomic-specific concerns previously discussed. Finally, this group seems to have achieved a full team, in which open and endovascular skill sets are combined not only in the performance of the procedure, but in the most critical aspect, the decision and planning stages.

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Institutional report - Vascular thoracic

Less-invasive management of left subclavian artery in stent-grafting for distal aortic arch disease☆

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Abstract

Simple coverage of the left subclavian artery (LSA) in thoracic endovascular aortic repair (TEVAR) is still a controversial procedure. We present our modified strategy dealing with LSA in TEVAR. Hand-made stent grafts were placed more proximal beyond the LSA for 104 patients. In elective 76, preoperative LSA occlusion test was performed on 31 patients, and preoperative computed tomographic angiography (CTA) of the vertebro-basilar artery was performed on the remaining 45. Head vessels were planned to be kept patent using fenestrated stent grafts, if possible. Stent grafts were placed from zone 0 in 23, zone 1 in 39, and zone 2 in 42. The LSA occlusion tests revealed harmful effects, such as loss of consciousness and vertigo in two out of 31 patients (6.5%). Vertebro-basilar arterial CTA revealed possible risks, if LSA covered, in three out of 45 patients (6.7%). Fenestrated stent grafts could successfully preserve 131 head vessels, except for one unintentional occlusion of the left carotid artery (0.75%). There was no LSA-related complication in any of the cases. A combination of preoperative vertebro-basilar arterial CTA and fenestrated stent grafts is useful to avoid possible LSA-related complications in TEVAR.

Keywords: Stent graft; Left subclavian artery; Vertebral artery; CT angiography; Thoracic aorta

1. Introduction

One of the major limitations to expand the indication of thoracic endovascular aortic repair (TEVAR) is an inadequate length of proximal landing zones because of clinically important head vessels branched from the aortic arch. Because of the unavailability of a commercial device with a fenestration or a branch to keep the head vessels patent after TEVAR, proximal extension of a proximal landing zone has been achieved by a simple coverage of the left subclavian artery (LSA) or revascularization of LSA using LSA bypass-grafting or transposition.

A recent review of TEVAR in which a stent graft was placed from zone 2 reported that revascularization of LSA should be recommended [1]. Although it is well recognized that possible risks following a simple coverage of LSA in TEVAR can be largely prevented by concomitant LSA revascularization [2], we still need to seek an even less-invasive treatment.

2. Material and methods

We began TEVAR by using a hand-made stent graft placed more proximal beyond the LSA (zone 2 [3]) from October 2001. By March 2008, 104 patients underwent TEVAR for distal aortic arch pathology. In elective cases, preoperative assessments were performed to evaluate an influence of possible coverage of LSA. In emergency cases, preoperative evaluation regarding possible LSA coverage was not carried out even if LSA was covered or could be preserved by a fenestrated stent graft.

Until April 2005, preoperative LSA balloon occlusion tests were conducted in cases in which there was a possibility that LSA was covered by a stent graft in elective TEVAR. Since May 2005, preoperative computed tomographic angiography (CTA) of the vertebro-basilar artery has been chosen as an initial screening to predict possible complications if LSA is simply covered. Therefore, a preoperative LSA occlusion test has been considered only for the cases in which preoperative CTA of the vertebro-basilar artery suggests possible complications if LSA is simply covered. The indication of TEVAR for distal aortic arch pathology is that a proximal end of the diseased aortic segment is >15 mm away from the left common carotid artery (LCC) and that a diameter of a proximal landing zone, the aortic arch, is <37 mm (Fig. 1).

The stent graft was custom-made and reconstructed by suturing graft material (Ube Corp, Ube, Japan) to an endoskeleton of Gianturco Z stents (Cook Inc, Bloomington, IN). Z-stents were attached to each other using stainless steel wires with solder, leaving spaces of 8–15 mm between stents so as to fit the configuration of the distal aortic arch

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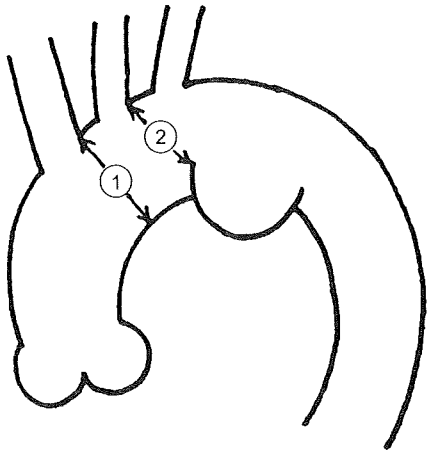

Fig. 1. Schema of distal aortic arch aneurysm. The indication of thoracic endovascular aortic repair is that a diameter of a proximal landing zone is <37 mm (1) and that a proximal end of the diseased aortic segment is >15 mm away from the left common carotid artery (2).

based on CTA images. A procedure of TEVAR in our institute was previously reported [13]. In cases in which LSA was located >15 mm away from the diseased aortic segment, LSA was kept patent using a fenestrated stent graft (Fig. 2). In cases in which the proximal edge of the diseased aortic segment or primary entry was located fewer than 15 mm away from LSA or in which LSA was involved in the aortic aneurysm, LSA was covered by a stent graft. LSA revascularization was considered if preoperative evaluation suggested a possible risk of neurological complications following a LSA simple coverage. When type II endoleak from LSA was preoperatively expected or seen in digital subtracted angiography (DSA) following stent-graft deployment, LSA was occluded using coil or a stent graft with one end stitched up before or after aortic stent-graft deployment.

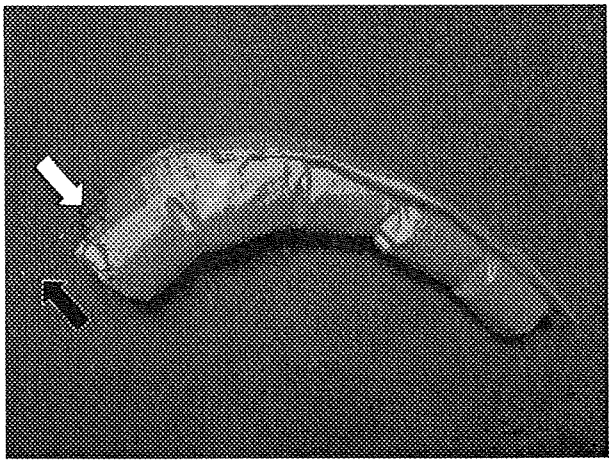

Fig. 2. A hand-made fenestrated stent graft. A proximal roof of a stent graft is fenestrated (white arrow) to preserve head vessels. A wire ring (black arrow) prevents distal migration of the device during stent-graft deployment. In a case of aortic dissection, a stent graft is often tapered to fit a size of a true lumen. A stent graft is custom-made to fit the distal aortic arch.

A procedure of LSA occlusion test was previously reported [13]. Briefly, during balloon occlusion of LSA for 20 min, neurological tests, including a finger-to-nose test were repeatedly performed to reveal possible adverse effects, such as cerebellar, brain stem, spinal cord or left arm ischemia.

A case in which the right or left vertebral artery (VA) measured above the posterior inferior cerebellar artery (PICA) was hypoplastic (Fig. 3), or in which the right VA was terminated (Fig. 4) or stenotic (Fig. 5), was considered to have the possibility of neurological complications if LSA is simply covered. In such a case, preoperative LSA balloon occlusion test or LSA revascularization was planned on the same day of TEVAR.

3. Results

In 76 elective cases out of 104 subjects, preoperative LSA occlusion tests were conducted on 31 and preoperative CTA of the vertebro-basilar artery was performed on 45. In 28 emergency cases (26.9%), preoperative evaluations regarding an influence of LSA coverage were not carried out regardless if LSA was covered or could be preserved by a fenestrated stent graft. The patients, aged 17–94 years (mean 70.2), consisted of 84 males (80.8%) and 20 females.

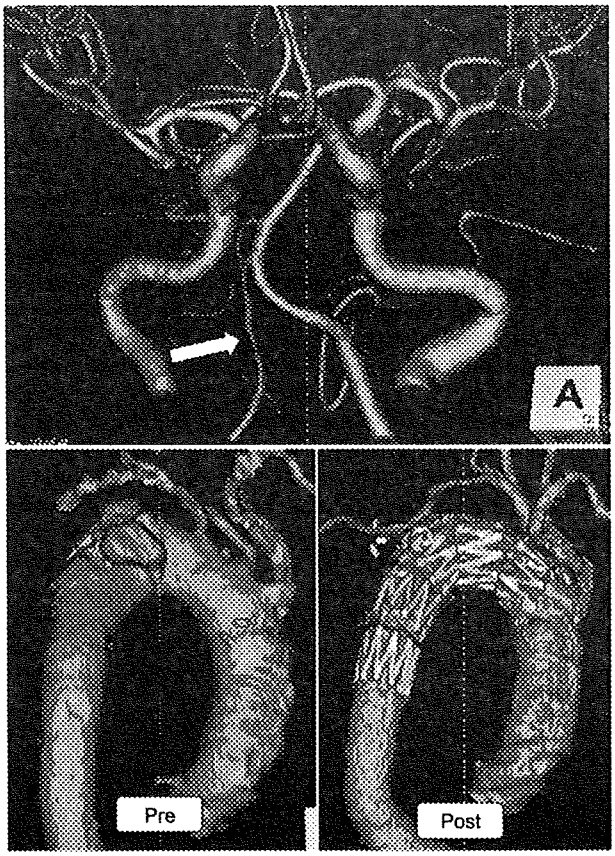

Fig. 3. Computed tomographic angiography (CTA) images. CTA of the vertebro-basilar artery revealed hypoplastic right vertebral artery (white arrow) (upper). A fenestrated stent graft well preserved antegrade blood flow into the left subclavian artery as well as the left common carotid artery (lower).

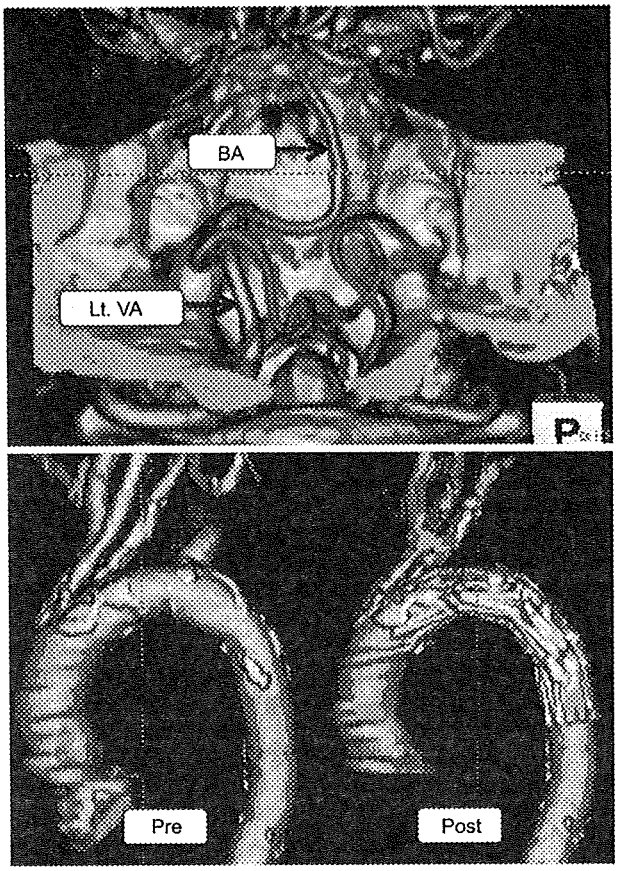

Fig. 4. CTA images. CTA of the vertebro-basilar artery suggested terminated right VA (upper). A fenestrated stent graft well preserved antegrade blood flow into LSA as well as LCC (lower). Lt. VA, left vertebral artery; BA, basilar artery.

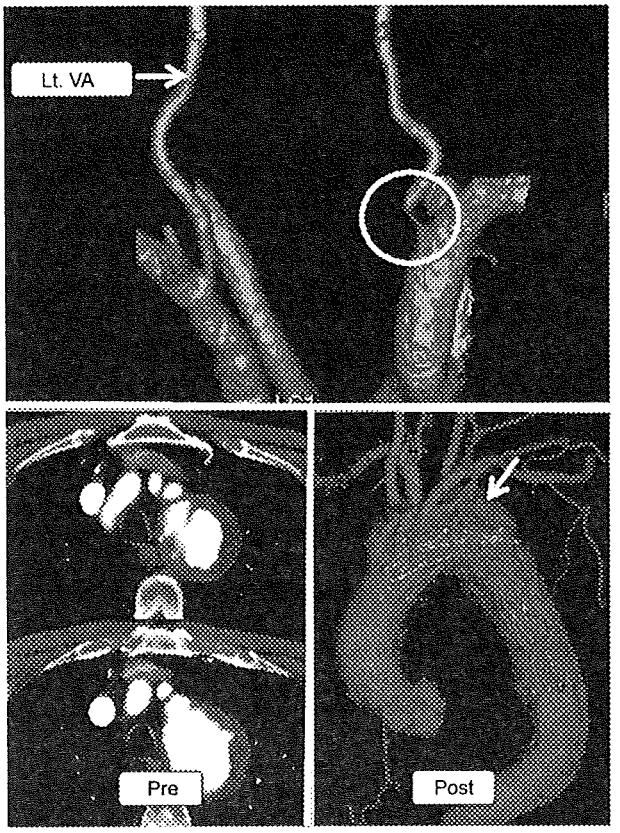

Fig. 5. CTA and CT images. CTA of the vertebral artery revealed stenotic orifice (white circle) of right VA (upper). A fenestrated stent graft well preserved antegrade blood flow into LSA as well as LCC (lower). Postoperative CTA shows complete thrombo-occlusion of distal aortic arch aneurysm (lower, white arrow). Lt. VA, left vertebral artery.

Distal aortic arch pathology consisted of degenerative thoracic aortic aneurysm in 55 (52.9%), type B aortic dissection in 20 (19.2%), thoracic aortic pseudoaneurysm in 28 (26.9%) and inflammatory thoracic aortic aneurysm in one (Table 1).

Stent grafts were placed from zone 0 in 23 patients (22.1%), zone 1 in 39 (37.5%), and zone 2 in 42 (40.4%) (Fig. 6). LSA was preserved by a fenestrated stent graft in 53 patients (51.0%) and revascularized by axillo-axillary bypass-grafting in 8 (7.7%) due to LSA occlusion tests being positive in two, patent left internal thoracic artery (LITA) graft in two and patient's discretion in four. LSA was simply covered by a stent graft in the remaining 43 patients (41.3%). Fenestrated stent grafts could successfully preserve 131 head vessels, except for one unintentional occlusion of LCC (0.75%). Fortunately, no neurological complication was observed in this 75-year-old man who additionally underwent LCC bypass-grafting following unintentional coverage of LCC.

LSA occlusion tests revealed harmful effects in two out of 31 patients (6.5%). A 71-year-old man lost consciousness several seconds after LSA occlusion. As soon as the occlusion balloon was deflated, his consciousness returned. A 76-year-old woman complained of vertigo a few minutes after LSA occlusion. LSA could not be preserved by a fenestrated stent graft due to a lack of distance between LSA and the diseased aortic segment in both cases. TEVAR was performed on these patients following concomitant axillo-axillary bypass-grafting.

CTA of the vertebro-basilar artery revealed possible risks, if LSA covered, in three out of 45 patients (6.7%). A 76-year-old woman with a hypoplastic right VA underwent TEVAR from zone 1 using a fenestrated stent graft (Fig. 3).

Table 1
Patient characteristics ($n=104$)

Age (years)	70.2±13.6 (17–94)
Male	84 (80.8%)
Pathology	
Degenerative aortic aneurysm	55 (52.9%)
Aortic dissection-related	20 (19.2%)
Pseudoaneurysm	28 (26.9%)
Blunt aortic injury	12
Ruptured degenerative	7
Ruptured aortic dissection	3
Anastomotic	6
Inflammatory	1 (1.0%)
Emergency	28 (26.9%)

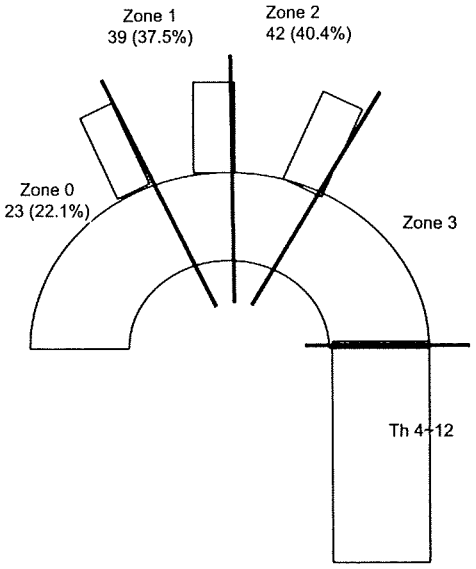

Fig. 6. Zone classification of a stent graft deployed from the aortic arch [3].

A 75-year-old woman with a terminated right VA underwent TEVAR using a fenestrated stent graft to preserve LSA although a preoperative LSA occlusion test was negative (Fig. 4). Finally, a 74-year-old man with a stenotic orifice of right VA underwent TEVAR using a fenestrated stent graft to preserve LSA without a preoperative LSA occlusion test (Fig. 5).

There was no LSA-related complication in any of the cases. Postoperative neurological complications included strokes in five patients (4.9%) and spinal cord ischemia in three (2.9%). Among five patients who suffered from strokes as an operative complication, two were treated using a fenestrated stent graft from zone 2 and 0 preserving LSA. The remaining stroke-complicated three patients were treated using a fenestrated stent graft preserving the brachio-cephalic artery (BCA) and LCC, but covering LSA. One of these patients suffered a stroke in the left VA region, but this was due to an embolism, not by LSA coverage. Delayed paraplegia was observed in two emergency rupture cases in which LSA could not be preserved due to the location of the aneurysm, and in one elective case which LSA was preoperatively occluded.

Two patients died due to an aortic aneurysm rupture or acute myocardial infarction in 76 elective cases (early mortality rate, 2.6%) and six patients in 28 emergency cases (21.4%). Excluding these early-death patients, 92 patients (95.8%) could be interviewed about post-TEVAR course, at least six months after operation by telephone or at out-patient clinic. We could not follow one patient until six months after TEVAR due to an unknown reason. Two patients underwent removal of stent grafts and open repair of thoracic aortic diseases three months and four months after TEVAR. One patient died due to cerebral hemorrhage five months after TEVAR. None of the patients, including 43 patients whose LSA was simply covered by a stent graft, have undergone any intervention to restore the blood flow into LSA in the follow-up periods.

4. Discussion

Previously, intentional occlusion of LSA was widely accepted in cases in which a proximal landing zone was too short to exclude distal aortic arch aneurysm in TEVAR [4,5]. However, it is obvious that LSA is anatomically important for some patients. A super-dominant or single left VA or VA that ends in PICA could be considered important anatomy, as could contralateral subclavian arterial disease. This anatomy would be particularly important in the presence of a circle of Willis that is incomplete, reportedly as high as 42.4% [6]. In another example, LSA is also very important for patients with previous coronary artery bypass-grafting with use of LITA. Although left arm ischemia immediately after LSA occlusion is very rare [7] and revascularization of intentionally occluded LSA was reported mainly in the follow-up periods [5], brain stem ischemia and paraplegia as complications following TEVAR [5,8] are different stories, which means these are too late to be treated at the time of diagnosis. According to a report [9] in which the anatomy of the cerebral arteries in 92 forensic medicine autopsies was assessed, the right VA measured above PICA was hypoplastic in 8.7% and the left VA in 7.6%. The right VA terminated to PICA in 3.3%. In 56.5%, either the left or right posterior communicating artery (PComA) was hypoplastic (or absent) and in 7.6%, both PComAs were absent. The authors concluded that there was a substantial risk of neurological complication following a simple coverage of LSA in TEVAR in 5.4% of the cases. This study indicates not only that there is a 5.4% risk following a simple coverage of LSA, but also that >90% of patients do not need LSA revascularization as an additional procedure in TEVAR.

As recent reports recommended [1,2], LSA revascularization is the easiest way to prevent LSA-coverage-related complications. However, LSA revascularization itself also has potential complications, such as vocal cord palsy, spinal cord ischemia, and a chance of infection [10]. Even LSA revascularization alone has a mortality rate of 2.6% [11]. Therefore, we believe that LSA revascularization should also be performed by endovascular techniques, such as a branched [12] or a fenestrated stent graft [13], if possible. Although a fenestrated stent graft cannot allow LSA revascularization for distal aortic arch aneurysm involving LSA, zone 2 cases can be treated using a fenestrated stent graft preserving LSA.

Although the report dealing with the subjects distal from zone 3 showed stroke rates of 2.2% [14], the report dealing with only zone 2 cases showed a rate as high as 8.6% [15], which was reported not to be related to LSA coverage. It seems obvious that more proximal stent-graft placement is related to a high incident rate of stroke. In our experience of 270 TEVAR by March 2008, there was only one patient (0.6%) who showed stroke symptoms following TEVAR in the group of zone 3 or more distal ($n=166$). However, the stroke incident rate was 4.8% as presented in this study. The prevention of strokes must be one of the important points to extend the indication of TEVAR for distal aortic

arch pathology. Spinal cord ischemia also happened in our subjects much like other reports, for example, often in emergency cases. We agree that unprotected LSA coverage increases an incident rate of spinal cord ischemia in TEVAR [2]. Despite two emergency rupture cases, an incident rate of spinal cord ischemia in 76 elective cases was 1.3%, which might mean that spinal cord ischemia does not happen frequently compared to strokes in TEVAR for distal aortic arch pathology.

In conclusion, a combination of preoperative vertebrobasilar arterial computed tomographic angiography and fenestrated stent grafts is useful to avoid possible LSA-related complications in thoracic endovascular aortic repair.

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Conference discussion

Dr. B. Zipfel *(Berlin, Germany)*: I wish to congratulate Dr. Kurimoto and his colleagues on their contribution to the problem how to manage the left subclavian artery when it has to be occluded by the stent graft. This remarkable series has good results of stent grafting in distal aortic arch disease.

Dr. Kurimoto and his colleagues were able to preserve the LSA in many cases, and in many cases, also more proximal head vessels by using handmade stent grafts with a scallop fenestration at the proximal end.

In elective cases the authors used an LSA balloon occlusion test to evaluate the cerebral perfusion dependent on patency of the LSA. This procedure was obviously abandoned after computer tomography angiography provided exact anatomical information on the vertebrobasilar artery. Only in cases of known anomalies or stenosis they performed additionally the occlusion test.

Using this policy, in 51% of the patients, the LSA perfusion was preserved by the scallop fenestration and an additional 7.7% with an axio-axillary bypass. In 43% of the patients, the LSA was simply covered with the stent graft. Eight neurological events, five strokes and three spinal cord ischemias are reported. Remarkably six of these events occurred in patients after simple coverage of the LSA.

This is basically the same experience we made. We use a little bit different approach because we are not so confident in fenestrated stent grafts. We use straight stent grafts, and in doubt we perform more general surgical revascularization using extrathoracic left carotid-subclavian bypass.

Now, this is my first question. After simple coverage of the LSA, 6 of 43 patients developed neurological complications that may be related to the LSA occlusion despite sophisticated preoperative workup of the vertebral circulation. How reliable is the balloon occlusion test of the LSA at rest in the cath lab, even if it is restricted to patients with identified abnormalities in the vertebral circulation? Don't you think that transcranial Doppler sonography might provide additional information?

Dr. Kurimoto: You are talking about the two cases of positive by occlusion test?

Dr. Zipfel: My question is whether this test is really reliable to identify potential problems from the LSA circulation, whether you should use additional information like a Doppler sonography.

Dr. Kurimoto: Yes. I really believe the occlusion test is reliable to predict the serious neurological complication. But occlusion test cannot predict possible delayed spinal cord ischemia or delayed claudication of the left arm.

But, yes, really critical neurological complications I think is very important to predict preoperatively.

Dr. Zipfel: You used stent grafts with a proximal scallop fenestration in a significant part of your distal aortic arch implantations. What is your experience in sealing of these grafts at the proximal end? How many Type I endoleaks did you experience?

Dr. Kurimoto: Endoleak?

Dr. Zipfel: Yes.

Dr. Kurimoto: It is one of the major concerns, but we experienced probably 15% of Type I endoleak. But only less than 5 patients underwent open conversion. Just we observed the size of aneurysm. If aneurysm size is increasing, we suggest the patient undergo open conversion.

Dr. E. Saadi *(Porto Alegre, Brazil)*: When you cover the left subclavian artery, you may have Type II endoleak by retrograde flow. Did you have any in your experience, and if yes, how did you treat it?

Dr. Kurimoto: If the left subclavian artery is branched from aneurysm, it is definitely necessary to embolize using the coil or something else.

But if the left subclavian artery is branched from normal arch wall, it isn't necessary to coil-embolize because the stent graft completely seals the left subclavian artery root.

So we don't see any Type II endoleak if the left subclavian artery branched from normal wall.

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Adamkiewicz動脈のCTAとMRA

吉岡　邦浩　　田中　良一

要　旨：最近のCTAとMRAの進歩はAdamkiewicz動脈の非侵襲的画像診断を可能とした。これらの方法を用いて診断を行う場合には，Adamkiewicz動脈と前根髄質静脈を正確に区別することが特に重要である。CTAは三次元表示や側副血行路の描出に適しており，MRAは解離性大動脈瘤においてAdamkiewicz動脈を分岐する肋間動脈が偽腔から起始する場合の描出に優れている。

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Key words: Adamkiewicz artery, CT, MRI, angiography

はじめに

近年のCT，MRIはハード，ソフト両面ともに進歩がめざましい。特にマルチスライスCTを用いたCT血管造影(CT angiography: CTA)とMRIの技術を用いたMR血管造影(MR angiography: MRA)は，心臓血管領域では侵襲的な血管造影法に匹敵する診断精度を持つまでに発展している。一方，胸(腹)部大動脈瘤の症例において，術後対麻痺の回避を目的としてCTAやMRAを用いて，Adamkiewicz動脈を手術前に同定する試みが広まりつつある。本稿では，これらの非侵襲的な診断法を用いてAdamkiewicz動脈の診断を行う場合の注意点，その診断精度，将来展望について解説する。

Adamkiewicz動脈の解剖

Adamkiewicz動脈は，脊髄の尾側1/3を栄養する太さ1mm前後の細い動脈で，大前根髄質動脈(great anterior radiculomedullary artery)の別名であり，これを最初に報告したポーランド生まれの病理学者であるAlbert Wojciech Adamkiewicz(1850〜1921)にちなんでいる。解剖学的にAdamkiewicz動脈を分岐する肋間あるいは腰動脈の位置は個体差が大きいことが知られており，本邦の剖検例での検討では第8肋間動脈から第1腰動脈の間で分岐するものが91%で，左側から分岐する確率が72%と報告されている[1]。その走行経路は概ね次のようである。下行大動脈から分岐した肋間(腰)動脈は椎体の外側で前枝と後枝に分かれる。前者は肋骨に沿って走行するのに対し，後者は脊柱管内へと向かう。その後枝は根髄質動脈，筋枝，椎体枝に分かれ，根髄質動脈はさらに前根髄質動脈と後根髄質動脈に分かれる。前根髄質動脈は脊髄の前根に沿って脊柱管内に入り，脊髄の前面を頭側に向かって斜走した後に前脊髄動脈と合流する。この前根髄質動脈は複数存在するが，その中で最も太いものが大前根髄質動脈，即ちAdamkiewicz動脈である。Adamkiewicz動脈が前脊髄動脈と合流する際には特徴的な"ヘアピンターン(ヘアピンカーブ)"を描く。この特徴的な形態がCTAやMRAでAdamkiewicz動脈を診断する際の重要な目印となる。

侵襲的画像診断法(血管造影)

CTAやMRAが登場する以前は，血管造影がAdamkiewicz動脈を診断する唯一の方法であり，カテーテルを用いて左右の肋間(腰)動脈を1本ずつ選択して造影する必要があった。しかし，手術適応を有するような大きな大動脈瘤や大動脈解離を持つ症例では，手技的に施行が困難であるばかりでなく，破裂や血栓症等のリスクを伴うためにわが国で行われることはほとんどなかった。しかし，ヨーロッパからは血管造影によるAdamkiewicz動脈

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診断の報告が散見される。ところが，480例という多数の症例を対象とした最近の検討でも，Adamkiewicz動脈の診断率は86%と高かったものの，瘤破裂による死亡が2例，対麻痺を含む重大な合併症も1.2%に発生したことが報告されている[2]。

このような背景から，非侵襲的画像診断法であるCTAやMRAによるAdamkiewicz動脈の診断に期待が寄せられていた。

非侵襲的診断法(CTAとMRA)

(1)注意点：動静脈の区別

CTAやMRAでAdamkiewicz動脈の診断を行う際に最も留意しなければならないのは，動脈(Adamkiewicz動脈)と静脈(前根髄質静脈)を厳密に区別することである。CTAでもMRAでも，描出された血管(この場合はAdamkiewicz動脈)が，必ずしも正確に動脈相で撮影されているとは限らず，動静脈が混在して描出されるタイミングで撮影されていたり，場合によっては静脈だけが描出されていたりする場合もあり得る。そのうえ，形態的にAdamkiewicz動脈と前根髄質静脈は非常に類似しており，両者の区別は容易ではない。解剖学的には，Adamkiewicz動脈は前脊髄動脈と合流する際に急峻な角度で"ヘアピンターン"を描くのに対し，前根髄質静脈と前脊髄静脈が形成する角度は動脈より鈍角で"コートフック"状と形容されている。しかし，実際の臨床上では典型例はむしろ少なく，このような形態のみを根拠として診断を行うことは非常に困難である[3]。繰り返すが，"ヘアピンターン"という形態だけで診断を行った場合には，常に前根髄質静脈を誤ってAdamkiewicz動脈と判定している危険性を孕んでいることに留意しなければならない。

今のところ，形態以外の情報で動静脈の区別を行う方法として，次に述べる2つの工夫がある。一つは，画像処理の技術を用いて大動脈から肋間動脈を経て，Adamkiewicz動脈，そして前脊髄動脈へと至る経路の連続性を証明する方法である。もう一つは，同じ場所を経時的に複数回撮影する，いわゆるダイナミック撮影(多相撮影)を行って動静脈を区別する方法である。それぞれの方法の詳細は次のCTAとMRAの項目の中で述べる。

(2)CTA

マルチスライスCTを用いて造影CTを行うが，非常に細い血管が検査の対象となるので，できるだけ薄いスライス厚で撮影することが望ましい。また，造影剤も通常の大動脈瘤や大動脈解離の診断のときとは異なり，高濃度の非イオン性のヨード造影剤を通常量より多く使用する必要がある。われわれの施設では，370mgI/mlの高濃度造影剤を秒間3.5mlの注入速度で，注入量2.0ml/kgのプロトコールを用いている[4]。一方，Utsunomiyaらは中濃度と高濃度の造影剤を比較した検討を行い，350mgI/mlの造影剤を秒間5.0mlで100mlを注入した場合がAdamkiewicz動脈の描出率が最も高かったと報告している[5]。

CTAでAdamkiewicz動脈を診断する手順は以下のようである。まず，MPR(multiplanar reformation)画像を用いて脊髄の前面でヘアピンターンを描く血管を探索する(**Fig. 1A**)。それが見つかったら，上流方向(大動脈方向)へ連続性に注意しながら追跡する。最終的にはCPR(curved planar reformation)画像を用いて，前脊髄動脈—Adamkiewicz動脈—根髄質動脈—肋間動脈の後枝—肋間動脈—大動脈を「一筆書き」のように描出し連続性を証明する(**Fig. 1C**)。この方法では解剖学的位置関係が失われるが，これを補うにはVR(volume rendering)法を用いた三次元画像(**Fig. E**)を追加することも有用である[6]。

大動脈瘤や大動脈解離等の大動脈疾患を有する症例を対象とした研究でのCTAによるAdamkiewicz動脈の診断能を**Table 1**に示す。

(3)MRA

MRAでのAdamkiewicz動脈の診断方法には2つの方法がある[8]。一つは空間分解能を重視したhigh spatial resolution MRAで，造影剤を0.2ml/秒程度で緩徐に持続注入しながら撮像することからslow infusion法とも呼ばれる。この方法では高い空間分解能を生かして，CTAと同様に大動脈からの連続性を証明することで動静脈の識別を行う(**Fig. 1B, D**)[3,4]。

もう一つは，時間分解能を重視するtime-resolved MRAと呼ばれる方法で，造影剤を秒間3～4mlのスピードで急速注入しながら1回あたり20～60秒程度の高速撮像法を用いて，同じ場所を多時相(ダイナミック)撮像する方法である[8-10]。この方法では造影剤の動態を経時的に観察できるので動脈相と静脈相を区別することができる。

MRAは放射線被ばくがなく，使用する造影剤の安全性が高い，骨構造の影響を受けない等の利点があるが，CTAと比較して撮像に技術と熟練を要するのが大きな問題

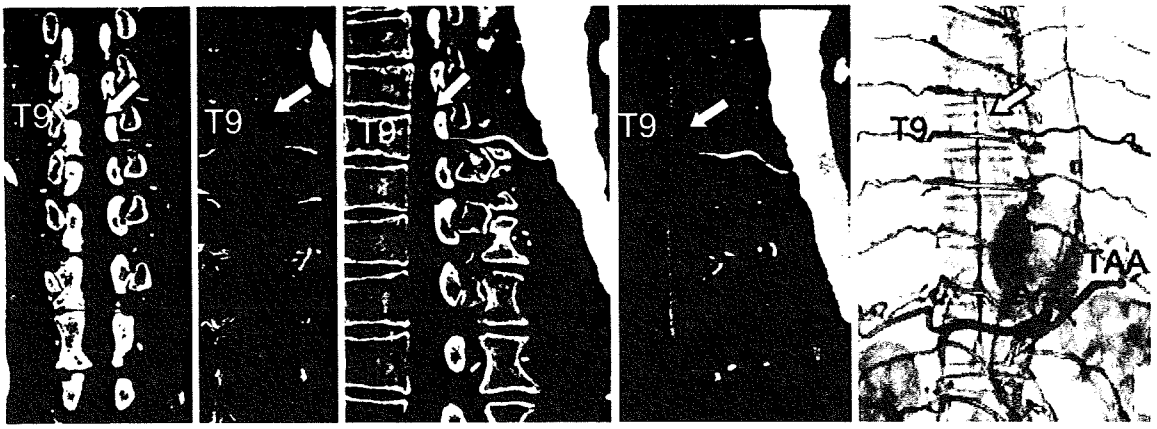

Figure 1 Identification of the artery of Adamkiewicz in a patient with thoracic aortic aneurysm.
A: Oblique coronal multiplanar reformation (MPR) image from CTA shows the artery of Adamkiewicz (arrow). This artery has a characteristic hairpin turn connection with the anterior spinal artery.
B: Oblique coronal MPR image from MRA shows the artery of Adamkiewicz (arrow).
C: Curved planar reformation (CPR) image from CTA shows continuity of the aorta, left 9th intercostal artery, radiculomedullary artery, the artery of Adamkiwicz (arrow), and anterior spinal artery.
D: CPR image from MRA shows the entire sequence from the aorta to the artery of Adamkiewicz (arrow) and anterior spinal artery.
E: Three-dimensional volume-rendered (VR) image from CTA, displayed with a semitransparent skeletal system and aorta. Arrow indicates the artery of Adamkiewicz.
T9: 9th thoracic vertebra, TAA: thoracic aortic aneurysm

Table 1 Detection rates for the artery of Adamkiewicz by CTA

	No. of patients	No. of detector rows	Slice thickness (mm)	Detection rate (%) by hairpin turn	Detection rate (%) by continuity
Takase K et al, 2002[7]	70	4	2	90	29
Yoshioka K et al, 2003[4]	30	4	1	80	50
Yoshioka K et al, 2006[3]	30	16	0.5	83	60
Utsunomiya D et al, 2008[5]	20	64	0.5	80	50

Table 2 Detection rates for the artery of Adamkiewicz by MRA

	No. of patients	Method	Detection Rate (%) by multiphase imaging	Detection Rate (%) by continuity
Yamada N et al, 2000[9]	26	Time-resolved MRA	69	—
Hyodoh H et al, 2005[10]	50	Time-resolved MRA	84	—
Yoshioka K et al, 2003[4]	30	High Spatial Resolution MRA	—	57
Yoshioka K et al, 2006[3]	30	High Spatial Resolution MRA	—	80

点である。**Table 2** に大動脈疾患を有する症例を対象とした報告でのMRAによるAdamkiewicz動脈の診断能を示す。

(4)CTA vs. MRA

CTAとMRAはそれぞれに利点と欠点を有しているが，大動脈瘤の手術を前提としてAdamkiewicz動脈を診断する場合を想定すると，われわれは次に掲げる事項が重要と考えている。

1)側副血行路の描出(CTA > MRA)

高度の動脈硬化等によってAdamkiewicz動脈を分岐す

Table 3 Comparison of CTA and MRA

	CTA	MRA high spatial resolution method	MRA time resolved method
Proof method	Continuity	Continuity	Multiphase imaging
Technique	Easy	Hard	Moderate
Interruption by osseus structure	Yes	No	No
Demonstraion of the collateral circulation	Good	Partial	Partial
Aortic dissection (False lumen origin)	Poor	Good	Good
3D demonstration	Good	Fair	—

る肋間(腰)動脈が閉塞し，側副血行路が形成されていることがある。閉塞部位は，そのほとんどが大動脈からの起始部である。このような症例は決して稀ではなく，われわれの施設の検討では23%の頻度で認められた[3]。さまざまな経路の側副血行路が形成されるが，肋間(腰)動脈の筋枝を介するものが多い。このような側副血行路はCTAでもMRAでも描出が可能である。しかし，MRAは撮像範囲が脊柱管の周囲に制限されるために，この範囲を超えて形成される側副血行路は描出できない弱点がある。例えば，肋間動脈の前枝の末梢部を架橋するルートや内胸動脈を経由するようなルートはMRAでは描出が不可能な部分が生じる。しかし，視野に制限のないCTAではそのルートの全容を描出することができる[3,11]。

2)偽腔開存型大動脈解離への対応(CTA < MRA)

偽腔開存型大動脈解離では，肋間(腰)動脈は真腔からも偽腔からも起始し得る。Adamkiewicz動脈を分岐する肋間(腰)動脈においても同様である。もし，Adamkiewicz動脈を分岐する肋間(腰)動脈が偽腔から起始している場合には，CTAでのAdamkiewicz動脈の描出は非常に困難な場合が多い。それは，偽腔内の血流は遅延しており造影タイミングの最適化が困難なことと，手術適応を有するような解離性瘤では偽腔の拡大が著しいために，偽腔内の造影剤が希釈されてしまうためである。われわれの施設の検討でも，解離性大動脈瘤におけるAdamkiewicz動脈の描出率は，連続性の証明を診断根拠とした場合に，MRAでは92%であったのに対してCTAではわずか58%であった[3]。

3)三次元表示(CTA > MRA)

Volume rendering(VR)法を用いた三次元表示は大動脈瘤や大動脈解離の病変の広がりや周囲組織との解剖学的な位置関係の把握に有用である。同様に，Adamkiewicz動脈を分岐する肋間(腰)動脈の位置の把握にも有用である。Adamkiewicz動脈の高さの診断のみならず，それを分岐する肋間(腰)動脈と大動脈(瘤)との位置関係，主要な分枝(例えば腹腔動脈)との位置関係を立体的に知るうえで三次元画像は役に立つ。この画像は，手術を実際に行う外科医と情報を共有し，手術方法や術式を検討するうえで特に有用である。このような画像を得るのには空間分解能に優れ，骨組織や石灰化の情報も得られるCTAの方が適している。

Table 3 にCTAとMRAの利点と欠点の要点を示す。このように一長一短のあるCTAとMRAではあるが，もし同一症例に対して両方の検査を行うことができれば，Adamkiewicz動脈の診断能は，連続性の証明を診断根拠とした場合でも，90%と非常に良好な成績が報告されている[3]。この診断能は侵襲的な血管造影法に匹敵する。

将来展望

CTでは，320列という超多列のマルチスライスCTや，現在よりも高い空間分解能を有する新型の装置が既に稼働している。これらがAdamkiewicz動脈の診断に用いられれば，前者ではワイドな検出器を生かしたダイナミック(多相)撮影による動態診断が可能となるであろうし，後者の高空間分解能は細いAdamkiewicz動脈の診断には打って付けで，例えば連続性の証明が容易になることから診断能の向上が期待される。

MRIでは，高磁場(3テスラ)装置が普及しつつあるが，この装置では，信号・ノイズ比や空間分解能の向上が可能である。一方，現在の1.5テスラ装置でも非造影MRAが急速に進歩しており，これをAdamkiewicz動脈の診断に応用する試みも始まっている。

これらの方法が実現されれば，現在よりも診断能が向上するであろうし，より容易に診断ができるようになるものと思われる。

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CT Angiography and MR Angiography of the Artery of Adamkiewicz

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Key words: Adamkiewicz artery, CT, MRI, angiography

New developments in CT angiography (CTA) and MR angiography (MRA) enable non-invasive diagnosis of the artery of Adamkiewicz. It is very important to differentiate the artery of Adamkiewicz from the anterior radiculomedullary vein in both CTA and MRA.

CTA is suitable for three-dimensional demonstration and visualization of the collateral circulation to the artery of Adamkiewicz.

MRA is superior for depiction of the artery of Adamkiewicz when it arises from false lumen of a dissecting aortic aneurysm.

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応用論文

大血管手術の安全性を高める画像支援ナビゲーションシステム

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Development of an Image-based Navigation System to Improve the Safety and the Reliability for Aortic Vascular Surgery

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Abstract --- To facilitate the accurate orientation of the surgical fields, we had developed a Multidimensional CT-based navigation system and clinically applied in thoracoabdominal aortic aneurysm repair with selective reconstruction of Adamkiewicz artery. Thirty patients who had thoracoabdominal aortic aneurysm were studied using Multidimensional CT imaging to identify their Adamkiewicz artery preoperatively. During navigation, the pointer location was measured by the sensor in the surgical field, and simultaneously, anatomical structures were visualized by the three-dimensional images. Then the position of the targeted intercostal arteries were successfully found in the real field, the targeted arteries and major visceral arteries were reconstructed. Hospital deaths were one patient and there was no paraplegia. A new navigation system was effective to improve an accurate orientation. Our clinical experiences exhibited that this system for thoracoabdominal aortic aneurysm repair provides a safe and effective surgery.

Keywords: aortic vascular surgery, surgical navigation system, three-dimensional imaging

1 はじめに

手術を行う際，医師には患者の解剖学的所見をもとに，実際に見えない血管や骨格構造を正確に把握し，手術の目的とする部位にアプローチする能力が求められる．この医師が見ている部位から目的部位までの位置関係を把握する能力を支援する手術ナビゲーションシステムが開発されている．これは，患者の身体の上で指し示すポインタの先端を CT や MRI の画像上にリアルタイムで表示し，目的部位とポインタの位置の関係を明確にすることで視覚的に支援するシステムである．

手術ナビゲーションは，脳神経外科，整形外科，放射線治療，耳鼻科等で利用されており，商用のシステムもある[1][2]．ナビゲーションの施行には，画像空間と手術中の患者空間との位置合わせ（レジストレーション）が重要な要素となる．そのため，対象とする臓器の形状や動きが無視できるほど小さいことを利用し，精度の向上を行っている．商用で用いられる治療領域ではレジストレーションに剛体とみなせる骨を用いている．例えば，骨の形状を多点計測して画像を最適な位置に合わせる方法や，骨の上にレジストレーション用のマーカを打ち込んで，手術中に画像を撮像し，マーカの位置も解剖学的構造とともに取得して位置合わせする方法が用いられている．これらの工夫により，1mm 以下のレジストレーション精度でナビゲーションを実現するシステムもある．

このように，手術ナビゲーションは精密さを要する手術を支援し，手術の安全性を向上させている．一方で，外科手術には，低侵襲手術が行えず，ほとんどが開胸

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や開腹を伴う手術である領域もある. そのひとつが胸腹部大動脈瘤手術である. 日本胸部外科学会の 2007 年の報告によれば, 2005 年に胸部大動脈瘤の手術は 8,907 件行われたが, うちステントによる低侵襲治療は1割程度で, ほとんどが開胸下の人工血管置換術となっている[3]. さらに開胸下に行われる手術は侵襲が大きく, 手術リスクも高く, 他科の手術に比べても難易度が高い. 胸腹部大動脈瘤の手術は, 死亡率が 7-11%で, 平均 9%ほどある. また, 命が助かっても合併症である対麻痺(下半身麻痺)になる危険性がある. その発生率は各施設によって異なるが, 2-27%ほどであり, 平均 10%と報告されている[4].

高リスクな手術の安全性の向上は切実な課題である. しかし, 全世界的にみても開胸・開腹を伴う手術に対応するナビゲーションシステムは十分な臨床応用が行われていない. それは, 開胸・開腹を伴う手術では, 臓器の位置・形状が変化しやすく, 一定精度での位置特定が困難なためである. そこで近年, 筆者らは, 独自に開発・臨床を重ねてきた脳腫瘍外科領域の手術ナビゲーションシステム[5] をベースに, 胸腹部大動脈瘤手術における手術リスクを低減し, 安全性向上を図るためのナビゲーションシステムを開発してきた[6].

手術リスクのひとつである対麻痺を防ぐには, 手術後も大動脈から脊髄への血流を十分に確保できることが重要である. それには大動脈から肋間動脈を通り, 脊髄へ血流を送る間に存在する Adamkiewicz 動脈を同定し, その血流を温存することが有効であるとされる[7][8]. まず, 事前の画像診断で Adamkiewicz 動脈の位置を特定し, そこにつながる肋間動脈を予め調べておく. そして, 手術中にその肋間動脈を特定し, 人工血管につないで血流を温存する. このとき, それ以外の肋間動脈の再建を省略して手術時間や大動脈遮断時間を短縮し, 作業効率をあげる. 画像技術の進歩で, 事前の画像診断で温存すべき肋間動脈を特定できるようになったが, 実際の患者を前にその肋間動脈の位置・走行を把握することは, 経験の多い医師でさえもときに難しいという.

そこで筆者ら開発したのが, Virtual Reality 技術を用いて MDCT(Multidimensional CT: 以下, CT)の画像を 3 次元再構築したモデルを利用するナビゲーションシステムである. これは, 手術者が重要と考え, 探索の目標にする血管と周辺の位置及び相対関係を正確かつ直感的に把握することを支援する. 文献[6]では, システムのプロトタイプを完成させ, 9 例の臨床応用を行った内容について報告した. 患者ごとに異なる血管の走行によって, レジストレーションに用いる特徴点の選択が限られ, ナビゲーションの水準に差が認められた. そこで, 特徴点の配置によってタイプ分類を行い, それぞれのナビゲーション水準を示した.

本論文では, その後に続けて行った 30 例の臨床結果をもとに, 次の 3 点によって臨床用システムの有効性を示す. 1) 重要な血管の位置をナビゲーションで特定できること, 2) 手術中に患者の体内で見えない血管の走行も CT 画像から血管・骨などの CG モデルを作成して呈示することで容易に把握できること, 3) 手術後の対麻痺の発生率である. そして, 3 名の医師がシステムを利用する間に見えてきた課題を示し, より臨床で使いやすいシステムへ改良した内容について報告する.

2 大血管ナビゲーションシステム

2.1 大動脈周辺の解剖学的位置関係

大動脈周辺の解剖学的位置関係を図 1 に示す. 大動脈(a)は身体の中心(体軸)を通る血管であるが, 体軸のやや左側に椎骨(b)に沿うように位置する. 脊柱は頚椎(cervical vertebrae), 胸椎(thoracic vertebrae), 腰椎(lumbar vertebrae)にわけられ, それぞれ 7 個(C1-C7), 12 個(Th1-Th12), 5 個(L1-L5)からなる. これら椎骨の間には椎間板があり, 胸椎には肋骨(c)が結合している. この肋骨の間に沿って存在する血管を肋間動脈(d)という. この肋間動脈から分岐し, ヘアピン状にカーブしながら脊髄(e)に血流を供給する血管が 1 本あり, それを Adamkiewicz 動脈(f)という. この Adamkiewicz 動脈の位置は個人差があるため, 手術前の診断画像から探しておく必要がある. こうして同定された Adamkiewicz 動脈につながる肋間動脈(グレー)が温存すべき血管(目標血管)であり, 大動脈内壁から見える開口部(g)のうち目標血管につながる開口部の位置(点線で囲まれた部位)をナビゲーションによって特定する.

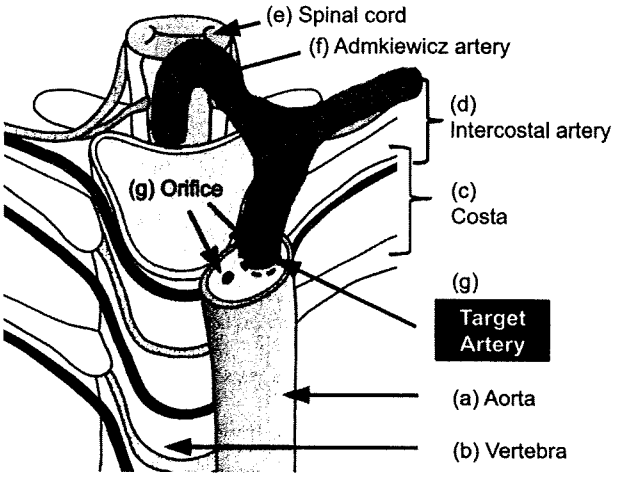

図1 大動脈周辺の解剖学的位置関係

Fig.1 Anatomical relationships between the aorta and the

2.2 本システムの特殊制約条件

大動脈手術を対象にしたナビゲーションシステムの構築にあたり，従来の商用ナビゲーションが臨床利用されている脳神経外科，整形外科などの手術と比べ，異なる条件を下記に示す．

1) 多量の出血や脳の虚血(血流が不足すること)を防ぐため，手術時間は限られる．特に，大動脈遮断後はナビゲーション設定にかけられる時間的余裕はない．

2) 時間・作業の制限から，手術中に MRI 画像を撮像し，確認することができない．

3) 画像と患者の実際の身体とで同一点であることを確実にするマーカをなるべく変形のない部位(骨など)に打ち込んで撮影することができない．

4) 画像撮影時と手術時では体位が異なる．

5) 重要な血管の位置と走行が確認できることが第一の目標である．

これらの条件を考慮し，ナビゲーションシステムは次のような仕様とする．

1') ナビゲーション設定は大動脈遮断前に行う．

2') 手術前に撮影した画像を用いる．

3') 手術者が手で触って見当をつけることができる解剖学的に特徴のある点をレジストレーション点とする．

4') 画像撮影時は仰臥位，手術時は側臥位であるが，患者への負担を考慮し，画像撮影はルーチンの範囲内で行う．大動脈は体軸に近く，目的血管の位置誤差が小さくなるレジストレーションを行う．

5') 血管走行を直感的に把握できるよう，画像はセグメンテーションを行った上で 3 次元的に表示する．

6') 温存する肋間動脈の位置は，血管の起始部を中心に半径 5.0mm の範囲(特に頭足方向)で特定することを目標とする．この値は，隣り合う血管と間違えない範囲として設定する．隣り合う血管の間隔は頭足方向に 20mm～30mm 程度であるため，その 4 分の 1(5.0mm)以内の位置ずれでは，十分に血管の位置を識別できる．

2.3 ナビゲーションシステムの構成

本システムは次の 4 つの要素，①ポインタ，②光学式 3 次元位置計測器，③ナビゲーション用 PC，④3 次元サーフェスモデル表示用 PC で構成される．これらの配置を図 2 に示す．①－④の数字は図中の数字に対応する．ポインタは光学式 3 次元位置計測器(Polaris®, Northern Digital Inc.)で手術室の実空間での任意の点を計測する際に用いる． 光学式 3 次元位置計測器はポインタが指し示した先端の位置，姿勢を計測すると，ナビゲーション用 PC に結果を送る．手術室の実空間とコンピュータ画像空間の患者モデルレジストレーションが行われると患者の画像空間で仮想ポインタが表示され，リアルタイムのポインタ位置が確認できる．CT 画像は 3 方向(Axial, Sagittal, Coronal)の断面図で表され，患部周辺の詳細な情報を確認するために用いる．また血管は細く長いため，断面によっては点となって表示されることがある．この場合，血管の走行を立体的にイメージすることが難しいため，3 次元サーフェスモデルも同時に表示させる．ナビゲーション用 PC と 3 次元サーフェスモデル表示用 PC は LAN ケーブルで接続されており，ナビゲーション用 PC から UDP 通信で送られてくるポインタの位置情報を 3 次元サーフェスモデル上でリアルタイムに更新，再描画する．図 3 は手術者が血管ファントムの肋間動脈の開口部の位置をポインタで指した際に 3 次元サーフェスモデルで確認している．

2.4 画像の種類と使用用途

患者体内の解剖学的情報の表示には，術前に診断用に異なるシーケンスで撮影した 2 種類の CT の画像を用いる．1 つは大動脈の走行を確認するために撮る画像(以下，大局画像)，もう 1 つは Adamkiewicz 動脈の位置を特定するために撮る画像(以下，局所画像)である．図 4 に大局画像，図 5 に局所画像の例を示す．大局画像は広範囲を撮影しているが，スライス厚が 1.5mm であり，肋間動脈の走行も確認できない．局所画像はスライス厚が 0.5mm であり，Adamkiewicz 動脈の描出が可能で，大局につながる肋間動脈を同定するのに十分なスペックである．大局画像は開胸前に肋骨のレベルと血管走行との位置関係を確認し，皮膚の切開位置を決定するために用いる．局所画像は開胸後，癒着部位等の剥離を行い，大動脈を露出させた後，実際に大動脈を遮断する前に重要な肋間動脈の位置と走行を把握するために用いる．

2.5 セグメンテーション

手術前の準備として，CT 画像のボリュームデータから関心領域を部位ごとに区別できるようにするため，セグメンテーションを行う．一連の作業はバイオメディカルイメージングソフトウェア(Analyze™, Mayo Clinic)を使用して行う．画像中の CT 値に応じて，大動脈，肋間動脈，骨といったそれぞれの領域を塗り分ける．基本は CT 値に基づく自動抽出を行うが，CT 値が重複して自動処理できない部位については手作業で抽出する．そして，各領域の輪郭を抽出して 3 次元再構築し，部位ごとのサーフェスデータへ変換する．

サーフェスデータの表示には，3 次元形状の描画に優れたライブラリである OpenGL を用いて自作したソフトウェアを用いる．色や透明度を変更可能とし，拡大縮小しながら 360° 自由な視点から表示することで，全体における各部位の位置関係を観察可能とする．この直感的な立体構造の表示法に加え，より詳細な解剖学的位置関係を把握可能とするため，ボリュームデータを上下，前後，左右の 3 軸方向の断層画像で表示し，同時に確認可能とする．

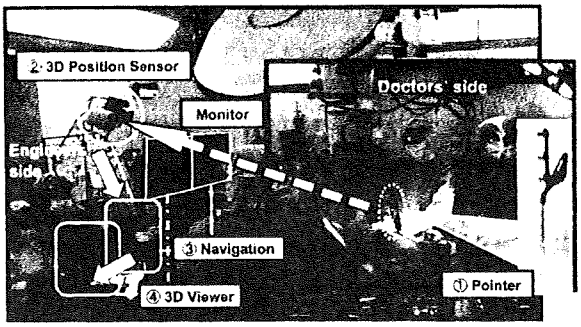

図 2. 手術室におけるナビゲーションシステムの配置
Fig.2 Layout of a navigation system in an operation room

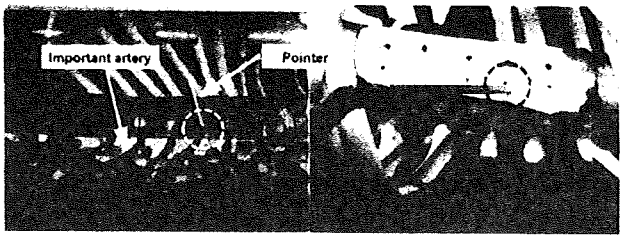

図 3. ファントムを用いた肋間動脈探索の様子
Fig.3 Searching an important intercostal artery (phantom)

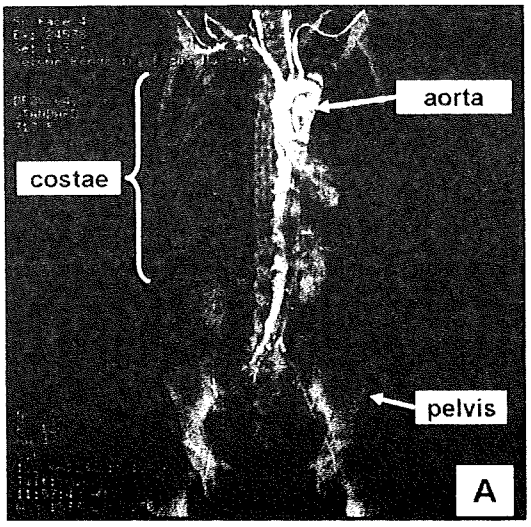

図 4. 大局画像
Fig.4 3D Image (Global)

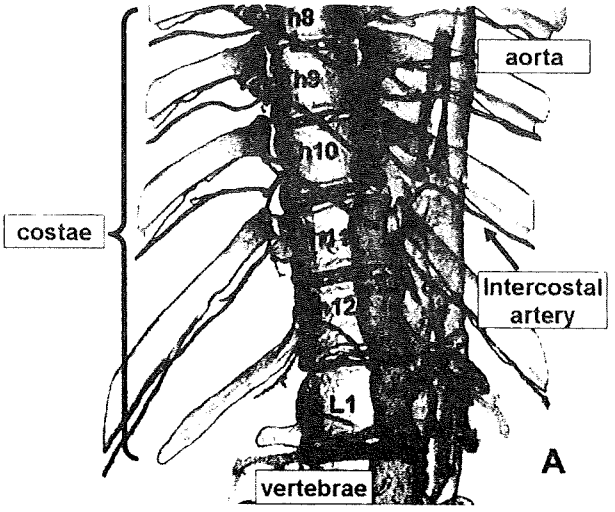

図 5. 局所画像
Fig.5 3D Image (Partial)

2.6 レジストレーション

コンピュータ画像空間の患者モデルと手術室の実空間の位置合わせを行うレジストレーションは，それぞれの座標空間で，3 次元位置測定装置を用いて位置を記録していく作業をいう．大血管ナビゲーションでは指定する点としては肋骨頭や椎骨側部の突起部などの解剖学的特徴点を指定する．3 次元空間の位置合わせを行うため，3 箇所以上の点の登録を行う．このレジストレーションに用いる点の候補と組み合わせについては 3.2 レジストレーション点の設定で示す．

レジストレーション誤差の算出法は以下の通りである．レジストレーションには対象範囲に応じて解剖学的な特徴点を n 点選択して用いる．画像上の解剖学的特徴点の点群を ${}^{i}\boldsymbol{P}$，ポインタを用いて実際に患者空間の特徴点を指して計測した点の点群を ${}^{p}\boldsymbol{P}$ とし，レジストレーション座標変換行列が ${}^{i}\boldsymbol{T}_{p}$ であるとき，計測点 ${}^{p}\boldsymbol{P}$ を画像座標によって求められた座系の点 ${}^{p}\boldsymbol{P}'$ に座標変換した値は式(2.1)で示される．

$$ {}^{p}\boldsymbol{P}' = {}^{i}\boldsymbol{T}_{p}({}^{p}\boldsymbol{P}) \qquad (2.1) $$

ここで，任意の特徴点を k 番目の点としたとき，画像空間上で選択した特徴点 ${}^{i}\boldsymbol{P}_{k}$ と実際に計測した点 ${}^{p}\boldsymbol{P}_{k}$ との誤差 $\Delta \boldsymbol{r}_{k}$ は式(2.2)で示される．

$$ \Delta \boldsymbol{r}_{k} = |{}^{p}\boldsymbol{P}_{k} - {}^{p}\boldsymbol{P}'_{k}| = |{}^{p}\boldsymbol{P}_{k} - {}^{i}\boldsymbol{T}_{p}({}^{p}\boldsymbol{P})| \qquad (2.2) $$

k=1 から n までの $\Delta \boldsymbol{r}_{k}$ を算出し，その平均値が最小となるときをレジストレーション誤差とし，システム信頼性の評価に用いた．

システム評価のためには目標部位の位置の精度を示すことがふさわしいが，大動脈切開後に肋間動脈の開口部の位置を毎回計測することは行っていない．患者の命が優先されるべき状況下で実際の手術とは異なる作業を増やすことは倫理的に困難であるためである．

目標とする領域を囲むように骨の特徴点を設定すれば，各骨の位置の誤差範囲内に血管の位置誤差があると考えられる．そこで，目標血管の誤差の代わりに骨のレジストレーション精度をシステム評価に用いることとした．

図 6 解剖学的特徴点(大局)

Fig.6 Anatomically specific points (Global)

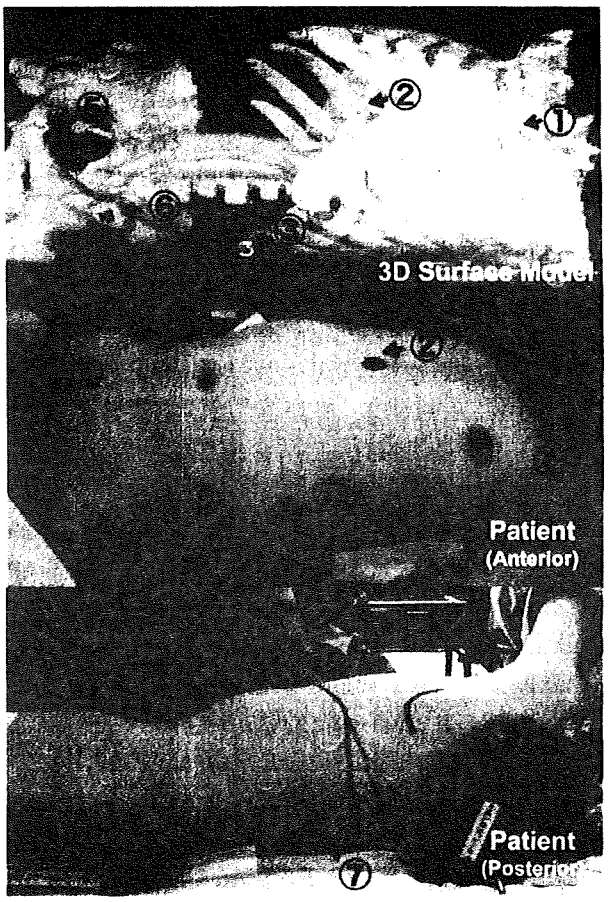

図 7 解剖学的特徴点(局所)

Fig.7 Anatomically specific points (Partial)

3 臨床応用

3.1 調査対象

2006 年 7 月から 2008 年 8 月までに東京女子医科大学で行われた胸部下行大動脈瘤および胸腹部大動脈瘤の人工血管置換術全 30 例で本システムを利用した. 初期の 21 例については, 局所画像のみを用いたナビゲーションを行っていたが, 開胸後に広い手術野を確保できない場合は画像で見るように明瞭にレジストレーションの位置を特定することは難しく, 限られた局所の領域を見て, 手探りで特徴点を探すことになる. そこで, 最近の 9 例については, 開胸前に体表上から体内の骨や血管の立体的位置関係を把握し, 作業を進めることができるよう大局画像を用いたナビゲーションを導入し, 局所画像を用いたナビゲーションを併用した.

また, システムの使用者は執刀医 1 名(熟練医師:手術者 A)と助手 2 名(中堅医師:手術者 B, C)とした.

3.2 レジストレーション点の設定

(1)大局画像によるナビゲーション

体軸に近く, 解剖学的に頭足方向の動きが小さく, 皮膚の上から触っても位置が確認できる特徴のある部位をレジストレーションに用いる.

特徴点は次の 8 部位を挙げた. ①胸骨角, ②剣状突起, ③左肋骨弓, ④左鎖骨頭, ⑤恥骨, ⑥左前腸骨棘, ⑦背中(Th11), ⑧背中(Th12). ここで, Th11, Th12 の肋骨は腹側の軟骨で固定されず, 開放状態にある. つまり, 左肋骨弓は 10 番の肋骨の軟骨の下端をさす. ①, ②, ④, ⑤, ⑦, ⑧は身体の中心, ③, ⑥は身体の中心から離れた位置にある. 基本的には, ターゲットとなる領域を囲むように体軸に近い 3 点で選択すれば誤差は小さくなる. 解剖学的特徴点設定の一例として, ①—③, ⑤—⑦の 6 点を設定したときを図 6 に示す.

局所画像によるナビゲーション

レジストレーション点は, ターゲットとなる肋間動脈の起始部の解剖学的特徴点を 3 点で囲むように設定する. 基本的には, ターゲットとなる肋間動脈が走行する肋骨を基準点(点①)とし, 1 レベル上の肋骨(点②), さらに①と②の間の椎骨(点③)とする. これらの点の配置を図 7 に示す. ①—③の数字は図中の数字に対応する.

これら特徴点は各症例に応じて適宜決定する. 重要な肋間動脈のレベルに応じて, 開胸の範囲が異なり, また, 患者の病変の状態によって大動脈の走行が異なることから, 手術視野が制限されるためである.

臨床経験より，骨上の点は解剖学的特徴点として利用するにも選択誤差が比較的小さかった．特に肋骨頭は医師の技量によらず認識しやすい点であった．これより，大動脈瘤の蛇行によって肋骨頭が視野から隠れてしまうときを除いて，肋骨頭を選択することとした．

4 結果および考察

4.1 大局画像によるナビゲーション

開胸前の大局画像を用いたナビゲーションの結果を表 1 に示す．9 回行っており，胸骨角，剣状突起，左肋骨弓の 3 点は必ず選択しているが，他の特徴点選択のパターンによって(1)から(6)までの場合にわけられる．特徴点の選択は○×で示す．○は該当あり，×は該当なしを意味する．

ナビゲーションを施行する上で，いずれの場合も隣り合う肋骨と間違えることはなかった．特に，胸骨角と剣状突起に関しては頭足方向に最もずれが大きいときでも 14.6mm であった．1本の肋骨の幅が約 20mm 程度であり，隣り合う肋骨との間隔もさらに約 10mm あることから，肋間レベルを特定できた．

胸骨角が第2肋骨の起始部，剣状突起が第7番肋骨の起始部にあたり，左肋骨弓が第10番肋骨の下端にあたるので，ターゲットがその範囲に含まれる場合は胸骨角，剣状突起，左肋骨弓この 3 点によるレジストレーションでも十分ナビゲーションが可能であった．

さらに，体軸方向の点である左鎖骨頭，恥骨を加えると，全体の誤差が減少したが，頭足方向の誤差を軽減できたためと考えられる．一方で，左前腸骨棘，背中の特徴点についても利用した．左前腸骨棘は背腹方向に誤差が大きかった．これは，患者の体位が画像撮影時の仰臥位から手術中に側臥位になることで捻転の影響を受けること，腸骨上の脂肪が重力方向に移動したことによると考えられる．また，背中の点については，体軸方向に近く，ターゲットとなる領域を囲む上でも適当な場所であると考えられるが，誤差は増大した．これは，画像取得時と手術中に同じ位置を選択することが難しかったためと考えられる．

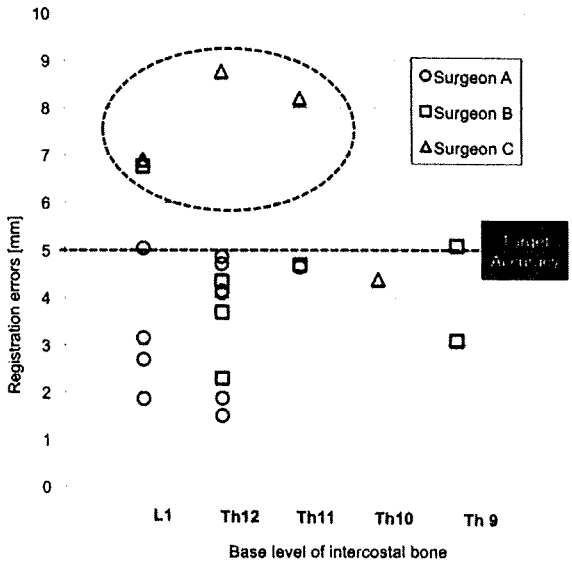

図 8 基準点に対するレジストレーション誤差(局所)

Fig.8 Registration Errors (Partial) in relation to a base point

表1 レジストレーション誤差(大局)

Table 1 Registration Errors (Global)

			特徴点選択のパターン					
			(1)	(2)	(3)	(4)	(5)	(6)
特徴点の部位	①	胸骨角	○	○	○	○	○	○
	②	剣状突起	○	○	○	○	○	○
	③	左肋骨弓	○	○	○	○	○	○
	④	左鎖骨頭	×	○	○	×	×	×
	⑤	恥骨	×	×	○	○	×	×
	⑥	左前腸骨棘	×	×	×	○	○	○
	⑦	背中(Th12)	×	×	×	○	○	×
	⑧	背中(Th11)	×	×	×	×	○	×
誤差[mm]		1回目	11.5	10.8	8.4	24.1	25.8	25.8
		2回目	13.3		11.7			
		3回目	16.5					

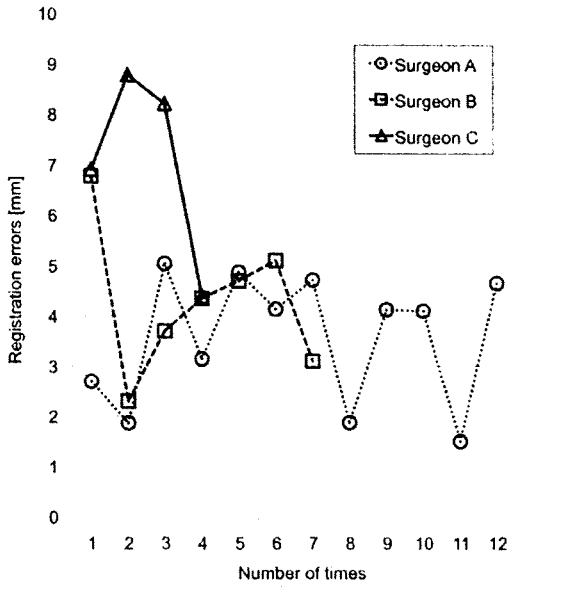

図 9 施行の順番に対するレジストレーション誤差(局所)

Fig.9 Registration Errors (Partial) in relation to number order