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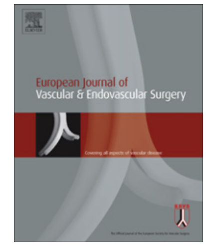

REVIEW

Advances in Imaging of the Spinal Cord Vascular Supply and its Relationship with Paraplegia after Aortic Interventions. A Review

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Submitted 19 March 2009; accepted 20 July 2009
Available online 27 August 2009

KEYWORDS
Spinal cord ischaemia;
Aorta;
Paraplegia;
Imaging;
Post-processing

Abstract *Introduction:* Preoperative knowledge of the spinal cord (SC) vasculature could be useful for stratifying and decreasing the risk of perioperative paraplegia after thoracic and thoraco-abdominal aortic surgery. Recent advances in magnetic resonance (MR) and computed tomography (CT) angiography and post-processing techniques have improved this knowledge.
Methods: A search of MEDLINE/Pubmed and SCOPUS databases identified 1414 pertinent abstracts; 123 full-length manuscripts were screened to identify relevant studies with acceptable design and patient numbers. Forty-three were selected.
Results: SC circulation was studied in 1196 patients to detect the great radicular artery: 522 by MR-angiography and 674 by CT angiography. Detection rates were 67—100% (mean 80.8%) with MR-angiography being 18—100% (mean 72%) with CT angiography. The side and level of the great radicular artery were consistent between the methods. Several authors tried to use the imaging results to guide clinical management.
Conclusions: Non-invasive imaging of the SC blood supply allows preoperative definition of the vasculature in many, but not all, cases. The impact of these findings on clinical management is potentially beneficial but still uncertain. Further improvements in image acquisition and post-processing techniques are needed. Future studies need to be large enough to compensate for inter-individual variability in SC vasculature in health and disease; however, even a partial reduction of paraplegia rate offers a formidable motivation for further research in this area.

Introduction

Spinal cord (SC) ischaemia is the most feared and dramatic complication of thoracic and thoraco-abdominal aortic procedures. Its incidence is significantly higher in extensive

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doi:10.1016/j.ejvs.2009.07.011

(Crawford type II) thoraco-abdominal aneurysms (TAAAs)[1–3] than in more limited descending thoracic aneurysms (DTAs). Endovascular procedures that do not require aortic cross-clamping have possibly reduced[4–7] but not abolished the incidence of paraplegia. SC ischaemia (paraplegia and paraparesis) after endovascular treatment of the thoracic aorta was described in 3.2% of 2872 patients reported in 20 articles between 1998 and 2008[8] and in 6.0% of 497 patients reported in three multicentre trials for Food Drug and Administration (FDA) approval of thoracic stent grafts.[9–11] Accurate patient selection, diligent planning and meticulous surgical technique are *sine qua non* for acceptable results. The aetiology of perioperative SC ischaemia is multi-factorial, and various efforts to reduce this complication have been made, including improving surgical technique[12] (sequential clamping,[13] prevention of steal phenomenon[13–15] and intercostal artery re-implantation[1,16,17]), adjuncts (distal perfusion,[2,3,13,17] hypothermia,[2,13] cerebrospinal fluid drainage,[2,3,7,13,18–21] etc.), monitoring (motor-evoked potentials[2,14,21–24]) and anaesthesia (rapid infusion systems, vital parameters monitoring,[7,13] arterial pressure management,[2,7,13,18,21] pharmacological strategies,[7,13] etc.).

Although strategies for preventing SC injury have evolved steadily since the 1980s, paraplegia has not been eliminated.[2,7,20,25,26] Accurate preoperative knowledge of the arterial supply to the SC would be extremely useful for procedure planning and risk stratification. Recent advances in imaging techniques, especially non-invasive techniques, have increased the possibility that this knowledge will soon be available for individual patients.[27]

Methods

MEDLINE/Pubmed and SCOPUS databases were searched using the keywords ALL ''Adamkiewicz'' OR ''arteria radicularis magna'' OR ''great radicular artery'' OR ''spinal artery'' AND ''imaging'' OR ''computed tomography'' OR ''magnetic resonance'' OR ''angiography''. The operator ALL searches the keyword in all the available fields (title, abstract, keywords, etc.); the operator 'OR' is used when the results must include one or more of the terms; documents that contain any of the words will be found. The operator 'AND' is used when you want the results to include all of the terms and the terms may be far apart. The search was restricted to four languages, English, French, Italian and Portuguese, and to the period between 1965 and February 2009.

Results

A total of 1414 abstracts were identified, 90% of which were published after 1992 and the most relevant of which were published in the past decade. Articles regarding intrinsic SC disease or vascular malformations of the SC were not relevant. The full texts of 123 potentially relevant articles were screened. We excluded case reports, anecdotal reports (patient population analysed <10), reviews, editorials, letters, animal studies and previous papers from the same group of authors when a more recent article with updated cases was found. The final selection was based on a review of the full publications of all studies that met the initial search criteria. Forty-three articles were included; additional papers are cited to support the Introduction and Discussion sections.

Catheter angiography

Digital angiography through selective catheterisation can provide high-quality images of the SC vasculature with excellent spatial resolution. Kieffer[28] reported 86% detection of the arteria radicularis magna (ARM) in 487 patients, Minatoya[26] in 60% of 109 patients and Williams[17] in 43% of 151 patients. However, this technique has significant drawbacks: it requires arterial catheterisation; it is time-consuming; and it is rather complex, particularly in patients with aortic disease, requiring a lot of diligence from the operator. Unfortunately, this technique is burdened by a small but non-negligible number of serious complications, including paraplegia and aneurysm rupture.[29] Catheter angiography has been used in this clinical setting in only a few institutions[17,26,28–32] (Fig. 1).

Magnetic resonance-angiography

Table 1 summarises the principal papers[16,23,24,33–38] regarding magnetic resonance (MR) angiography of the SC vasculature. The majority were published in radiology journals.

All reports concerned with patients with TAAA or DTA, with dissection being present in a variable number of cases.[22–24,33,34,36,38,39,50–59] The number of patients studied ranged from 23 to 170. Sex distribution (M = 459, F = 182) and age range (17–91 years; mean, 66 years) were consistent with the clinical setting. The ARM detection rate ranged from 67% to 100%. There was a trend towards higher detection rates in more recent studies,[16,23,37,38] larger studies,[38,40] and studies conducted in dedicated institutions[23,39,51,52,56] (several papers were from the same centre). Studies using multiple techniques had a higher overall rate of ARM visualisation.[35,37,39]

Segmental level of origin and lateralisation of the ARM are rather consistent and have been summarised in a recent publication.[27] The level and side of origin of the ARM as detected by MR-angiography in the papers that we reviewed are summarised in Table 2 and Fig. 1. Most of the patients analysed in these papers were surgical candidates, and some authors used the results of this novel imaging modality to try to improve clinical outcomes. The results regarding clinical relevance are summarised in Table 1.

Computed tomography-angiography (and post-processing tools)

Table 3 summarises the principal papers[27,35,37,39–49] regarding computed tomography (CT) angiography of the SC vasculature. Many reports dealt with patients with TAAA or DTA or aortic dissection; however, there are also recent studies in which patients without aortic disease were examined and they showed the best detection rate. The number of patients studied ranged from 10 to 100. Sex distribution (M = 379, F = 148) and age range (5–90 years; mean, 60.3 years) were consistent with the clinical setting. The ARM detection rate ranged widely, from 18% to 100%.

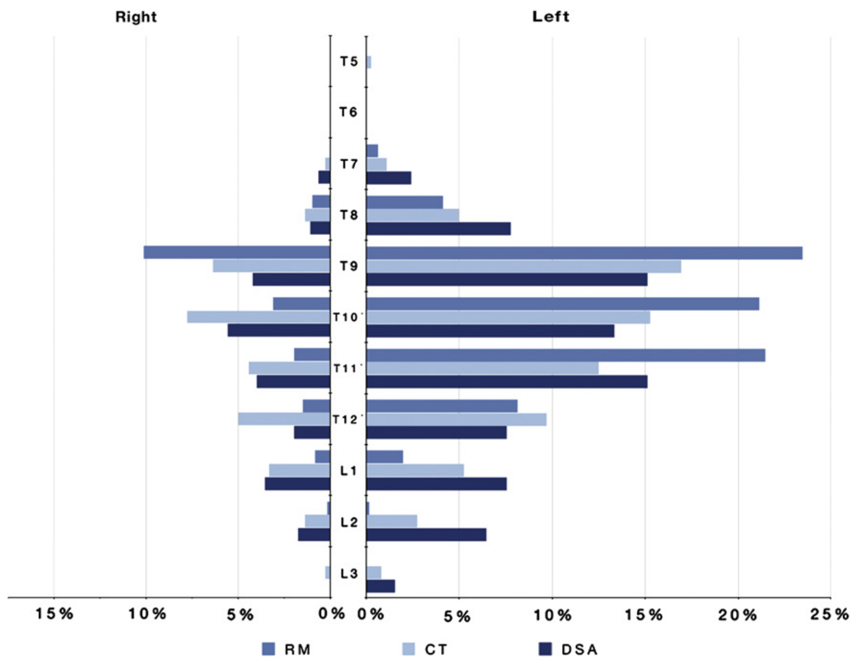

Figure 1 The level and side of origin of the arteria radicularis magna (ARM) when detected with magnetic resonance-angiography [16,23,24,33–38] (total ARM: 557), computed tomography-angiography[27,35,37,39–49] (total ARM: 334), and catheter angiography[28,32] (total ARM: 449).

As previously mentioned, studies using multiple techniques had a higher overall rate of ARM visualisation. Segmental level of origin and lateralisation were similar to those reported for MR-angiography studies.[27] The level and side of origin of the ARM as detected by CT angiography are summarised in Table 4 and Fig. 1.

Until recently, reformatting the CT dataset to obtain the desired images was possible only on dedicated imaging workstations and this resource is rather limited in most centres. The situation has changed considerably since 2004, in the past 2 years, in particular, with the creation of OsiriX software.[62] This software can be downloaded from the Internet for free and is dedicated to ''DICOM'' images (Digital Imaging and Communications in Medicine) produced by current medical equipment, including CT and MR, and runs on regular Mac OS × computers. As of the beginning of 2009, there are more than 37 000 users of OsiriX worldwide.[27]

Discussion

Anatomy

Detailed knowledge of normal anatomy of the SC blood supply and its extreme inter-individual variability is essential for accurate interpretation of images generated by all modalities and for beneficial assessment of the spinal vasculature in the individual patient with aortic disease. While excellent descriptions are available in several textbooks,[63] inaccuracies are also common in many handbooks and published articles,[18,64] and nomenclature for the same vessel often varies. As a result, confusion is widespread in this field, even among vascular surgeons. We encourage the readers to refer to the excellent textbook by Thron for detailed anatomical descriptions.[63]

In summary, segmental feeders to the SC originate from the aorta through the intercostal and lumbar arteries and subclavian and hypogastric branches. Intercostal/lumbar arteries divide thrice before reaching the SC: the first branch is the nervo-medullary (or radiculo-medullary) artery, which further divides into an anterior and a posterior radicular artery. While the latter division is constant to supply the anterior and posterior part of the vertebral canal, the nerve roots and the dura, only at certain levels do the anterior and posterior radicular arteries cross the dura and reach the medulla. In fact, only a few (range, 2–14; mean = 6) of these segmental branches remain in adults. The anterior radicular artery divides into a descending and an ascending branch. The anterior spinal artery, which is crucial for vascularisation of the grey matter, is an anastomotic channel between ascending and descending branches of neighbouring anterior radicular arteries. One anterior radicular artery is always distinctly dominant in calibre and therefore is called arteria radicularis magna, or great radicular artery or artery of Adamkiewicz. The posterior radicular artery has a similar pattern but produces two longitudinal anastomotic channels: the postero-lateral spinal arteries. Arteries directly supplying the SC are divided into a central system fed by the sulcal arteries and a peripheral system, the pial plexus (or pial network), giving origin to perforating branches.[63,64]

The interesting biography of Albert Wojciech Adamkiewicz, who discovered the variable vascularity of the SC over a century ago, can be found in recent publications.[65–67]

Magnetic resonance-angiography

MR Studies have been capable of visualising vessels that supply the SC since the year 2000. Visualisation of the

Table 1 Studies that identified the arteria radicularis magna (ARM) using magnetic resonance-angiography.[3,16,23,24,33–38]

Year	Author	PTS	Disease	Diss	Arm (%)	Age	M/F	Clinical relevance
2000	Yamada[33]	26	TAAA + DTA	11/26	18/26 (69)	60.5	19/7	No paraplegia in pts. studied with MR with selective IC re-implantation.
2002	Kawaharada[a,34]	40	TAAA + DTA	15/40	29/40 (73)	67	25/15	No paraplegia in 11 pts. studied with MR with selective IC re-implantation, 8% in 26 pts. previously ('94–'99) operated with no MR study and no cerebrospinal fluid drainage.
2003	Yoshioka[b,35]	30	TAAA + DTA	10/30	20/30 (67)	64	25/5	Same pts. also received CT-A with ARM detection of 80%. MR + CT: ARM detection (97%). No clinical results.
2005	Hyodoh[a,36]	50	TAAA	8/50	42/50 (84)	67.2	38/12	Paraplegia 4% only in patient with ARM not identified.
2006	Ogino[24] (Review 1998–2003)	92(−3)	TAAA(39) + DTA(53)	32/92	65/92 (71)	67	68/24	Overall 1.1% paraplegia (1/92). In 27/92 ARM was not identified, 1 pt had MEP reduction restored after "blind" re-implantation of T7-T9. In 65/92 ARM identified: 2 MEP reduction when ARM outside-clamping zone, 1 paraplegic after 80' clamping time with preserved ARM. In pts with ARM in clamping zone, in 6 pts. with MEP reduction selective IC re-implantation; MEP restored in all.
2006	Yoshioka[b,37]	30	DTA(18) + TAAA(12)	12/30	28/30 (93)	63.8	23/7	Same pts. also received CT-A with ARM detection of 83%. MR + CT: ARM detection 27/30 (90%). No clinical results.
2007	Nijenhuis[23]	60	TAAA(41) + DTA(19)	21/60	60/60 (100)	61	32/28	Overall 3.3% paraplegia (2/60). No paraplegia or MEP reduction when ARM outside-clamping zone (16/60). In pts with ARM in clamping zone (44/60), in 14/44 pts. with MEP reduction selective IC re-implantation; MEP restored in 12/14. N.B. Patent ARM but the segmental artery from aorta occluded at its origin in 40% of cases. (Aneurysm 21/39, dissection 3/21)
2007	Hyodoh[a,38]	170	TAAA	39/170	140/170 (82)	67	123/47	No clinical results
2008	Mell[16]	23(+4)	TAAA(19) + DTA(8)		20/23 (87)	65.2	19/8	No paraplegia with selective IC re-implantation after aortic de-clamping
	Total	522		133	422/522 (80.8)	65.5	372/153	

[a] Same authors as in Sapporo.
[b] Same authors but different groups of patients.

Table 2 Summary of magnetic resonance-angiography studies that reported the arteria radicularis magna (ARM) level of origin.

Author/Year of publication	Total		T7	T8	T9	T10	T11	T12	L1	L2	L3	Total
Yamada et al. 2000[33]	18	Left	0	2	7	1	3	0	0	0	0	13
		Right	0	2	0	1	0	1	1	0	0	5
Kawaharada et al. 2002[34]	29	Left	0	0	5	7	8	5	3	1	0	29
		Right	0	0	0	0	0	0	0	0	0	0
Yoshioka et al. 2003[35]	27	Left	1	2	8	7	3	1	0	0	0	22
		Right	0	0	2	3	0	0	0	0	0	5
Kawaharada et al. 2004[55]	108	Left	1	3	27	25	35	11	1	0	0	103
		Right	0	0	2	2	1	0	0	0	0	5
Hyodoh et al. 2005[36]	42	Left	1	3	8	9	17	3	0	0	0	41
		Right	0	0	0	0	1	0	0	0	0	1
Nijenhuis et al. 2005[56]	11	Left	0	0	2	2	2	2	0	0	0	8
		Right	0	0	1	0	0	0	1	1	0	3
Yoshioka et al. 2006[37]	29	Left	0	2	4	7	3	2	3	0	0	21
		Right	0	0	1	2	2	2	1	0	0	8
Ogino et al. 2006[24]	66	Left	1	6	23	10	5	3	3	0	0	51
		Right	0	1	48	4	3	1	2	0	0	15
Schurink et al. 2007[21]	9	Left	0	0	0	2	2	2	0	0	0	6
		Right	0	0	0	1	1	1	0	0	0	3
Hyodoh et al. 2007[38]	158	Left	0	6	48	40	43	14	0	0	0	151
		Right	0	2	3	1	1	0	0	0	0	7
Nijenhuis et al. 2007[23]	60	Left		1	9	17	8	6	2			43
		Right		1	4	5	3	4				17
Total	557		4, 0.7%	31, 5.5%	158, 28.3%	146, 26.2%	141, 25.3%	58, 10.4%	17, 3.05%	2, 0.35%	0	557

vascular anatomy of the SC supply requires both large spatial coverage (cranio-caudal FOV) and high spatial resolution, together with temporal resolution to differentiate arteries from veins.[53] The ability to discriminate between arterial supply and venous drainage is a clear advantage of MR-angiography; moreover, proximity to skeletal structures and body mass of the patient are irrelevant.

Special acquisition protocols are required for optimal results, particularly fast-acquisition contrast-enhanced techniques that use a strong (temporarily high concentration) bolus. Moreover, good skill and dedication in image post-processing are required. In some instances, these techniques have revealed collateral pathways that compensate multi-segmental intercostal artery occlusions due to aortic interventions.[22]

Although not tolerated by all patients and with several contraindications that may occasionally prevent its use, MR does not involve exposure to ionising radiation and has a very small risk for complications, making it a very attractive technique. The fact that, in most centres, CT is the technique of choice for studying the thoraco-abdominal aorta (especially in the endovascular era in which accurate measurements are required for preoperative planning and sizing) makes MR-angiography less practical in the real-life clinical environment.

Because the studies we reviewed analysed patients with a significantly diseased thoracic aorta (mainly atherosclerotic aneurysm or dissection), there is no way to determine how much the disease interfered with the capability of the method to detect the ARM. In Nijenhuis's study,[23] the only study that detected the ARM in all cases, the segmental artery from the aorta (intercostal/lumbar) was occluded in 40% of cases. Interestingly, the segmental artery was occluded in 21 of 39 patients with atherosclerotic aneurysm and in three of 21 patients with dissection.

Computed tomography-angiography

In a 1994 study,[68] the SC vasculature was visualised by contrast-enhanced CT. The anterior spinal artery was seen in 132 of 150 patients (88%) and the ARM in 41 of 150 patients (27%). However, improvements in CT scanners and post-processing techniques made during the past decade have allowed systematic detection of the ARM.[27,40,43,45]

Multi-detector row helical CT enables examinations that cover an extensive range in the cranio-caudal direction with thin collimation in a short time interval (excellent temporal and spatial resolution). Nowadays, millimetre-sized arteries are well within the detection capabilities of this technique[40]; however, the ARM detection rate reported in the literature reached or approached 100% only in a few studies. Technical limitations of CT data acquisition alone cannot explain the lack of detection of this particular vessel. Improved post-processing techniques need to be explored and our understanding of spinal vasculature in the presence of severe aortic disease must be advanced.

A shortcoming of CT-based imaging of SC vessels is that the vessels are surrounded by high-density skeletal formations. For CT angiography, the patient's body weight and conformation are important because the bodies of obese patients absorb more X-rays (fewer photons reach the

Table 3 Studies that identified the arteria radicularis magna (ARM) using computed tomography-angiography.[4,27,35,37,39–48]

Year	Author	PTS	Disease	Diss	Arm (%)	Age	M/F	Clinical relevance
2002	TAKASE[a,47]	70	AAA(20) + DTA(35) + OK(15)	19/70	63/70 (90)	68.4	54/16	No clinical correlation
2003	Yoshioka[35]	30	DTA + TAAA	10/30	24/30 (80)	64	25/5	Same pts. also received MR-A with ARM detection of 67%. MR + CT: ARM detection 90%. No clinical results.
2003	Kudo[41]	19	LIVER DISEASE	–	13/19 (68)	56.2	14/5	Notably the ASA was detected in all cases, the upper limit of the CT scan performed for liver disease could have been too low to detect ARM in several instances.
2005	Nishimura[60]	14	Retroperitoneal cancer, liver cancer, metastasis in vertebral bodies	–	12/14 (85)	65.6	9/5	No clinical correlation
2006	Yoshioka[37]	30	DTA(18) + TAAA(12)	12/30	25/30 (83)	63.8	23/7	Same pts. also received MR-A with ARM detection of 93%. MR + CT: ARM detection 97%. No clinical Results.
2006	Boll[40]	100	PANCREAS NEOPLASM	–	100/100 (100)	61.7	56/44	Prospective series, employed a modified brain vessel reconstruction algorithm, no vascular disease.
2007	Takase[a,46]	10	DTA(6) + TAAA(4)	5/10	9/10 (90)	61	9/1	No post-operative neurologic complications in these 10 pts.
2007	Nojiri[45]	27	DTA + TAAA	14/27	27/27 (100)	62.4	21/6	Intra-aortic administration of contrast media through 4Fr. catheter
2007	Nijenhuis[39]	39	DTA(16) + TAAA(23)	14/39	29/39 (74)	65	20/19	Operation with MEP monitoring. Paraplegia: 2/39. One early case in spite of re-implantation of relevant intercostals after MEP decrease. One delayed case after post-operative hypotension without intercostals re-implantation for bad quality aorta.
2007	Ou[42]	40	CHD	–	38/40 (95)	7.5	23/17	Performed with 64 row scanner on children studied for different congenital heart diseases.
2007	Von Tengg[48]	17	TAA(6) + Ulcer(2) + DISS(5) + Expanding DISS(5)	5	10/17(58)	63	13/4	Patients analysed before and after thoracic aortic endografting. The ARM were seen in 10/17 patients pre EVAR and 9/17 post EVAR.
2008	Nakayama	80	DTA(29) + AAA(26) + Takayasu(4)	0	45/80 (56.3)	672	50/30	No clinical correlation
2008	Uotani[43]	32	DTA(12) + TAAA(20)	11	25/32 (78)	68.1	22/10	No clinical correlation
2008	Utsunomiya[49]	80	TAAA + DTA	0	50/80 (62)	69.3	51/29	No clinical correlation
2009	Zhao[44]	99	An (31) + IH(5) + OK(18)	45	18/99 (18)	61.3	68/31	No clinical correlation
2009	Melissano[27]	67	DTA(17) + TAAA(36) + DISS(9) + Pseudo-Aneurysm(1)	9	45/67 (67.1)	65.6	57/10	No clinical correlation
	Total	754		144	533/754 (70.6)	61	515/239	

CHD, congenital heart disease.
[a] Same authors but different patients and equipment.

Table 4 Summary of computed tomography-angiography studies that reported arteria radicularis magna (ARM) level of origin.

Author/Year of publication	Total		T5	T7	T8	T9	T10	T11	T12	L1	L2	L3	Total
Takase 2002[47]	78	Left	0	1	6	14	1	14	9	6	3	0	54
		Right	0	0	1	5	6	3	4	2	3	0	24
Yoshioka 2003[35]	17	Left	0	1	2	8	7	3	1	0	0	0	22
		Right	0	0	0	2	3	0	0	0	0	0	5
Kudo et al. 2003[41]	13	Left	0	0	0	0	4	2	0	2	1	0	9
		Right	0	0	0	0	0	3	1	0	0	0	4
Nishimura et al. 2005[60]	16	Left	0	0	0	1	1	2	3	1	2	0	11
		Right	0	0	0	0	0	1	1	3	0	0	5
Yoshioka et al. 2006[37]	29	Left	0	0	2	4	7	3	2	3	0	0	21
		Right	0	0	0	1	2	2	2	1	0	0	8
Nojiri et al. 2007[45]	35	Left	0	0	0	5	4	2	3	2	2	3	21
		Right	0	0	1	3	5	0	0	4	0	1	14
Ou et al. 2007[42]	37	Left	1	0	4	15	5	2	0	0	0	0	26
		Right	0	0	2	6	2	0	1	0	0	0	11
Von Tengg et al. 2007[48]	10	Left	0	0	0	2	3	2	1	0	0	0	8
		Right	0	0	0	0	1	0	1	0	0	0	2
Nakayama et al. 2008[61]	10	Left	0	0	0	0	3	0	3	1	0	0	7
		Right	0	0	0	0	1	1	1	0	0	0	3
Uotani 2008[43]	25	Left	0	1	1	6	6	1	1	0	2	0	18
		Right	0	0	0	2	3	1	1	0	0	0	7
Zhao et al. 2009[44]	18	Left	0	0	1	3	3	4	2	0	0	0	13
		Right	0	1	0	1	0	1	2	0	0	0	5
Melissano et al. 2009[27]	62	Left		1	2	3	11	10	10	4	0	0	41
		Right		0	1	3	5	4	4	2	2	0	21
Total	334		1, 0.29%	6, 1.79%	23, 6.88%	84, 25.14%	83, 24.8%	61, 18.26%	53, 15.86%	31, 9.28%	15, 4.49%	4	334

detectors), which increases the noise and decreases both the signal-to-noise ratio and the contrast-to-noise ratio. This could explain some of the better results obtained in the Japanese population, which is leaner than the European one,[39,61] and the excellent results obtained in neoplastic patients[40,60] and in children with congenital heart disease.[42]

With CT angiography, some degree of uncertainty may exist in the differential diagnosis between artery (ARM) and vein, particularly because the anterior median vein draining to a radicular vein is similar in shape. This differentiation is especially difficult for the anterior SC vasculature, since the draining vein usually has a larger diameter and is detected more easily. For these reasons, Backes et al.[53] criticised the use of CT for evaluating the spinal vasculature based mainly on anatomical criteria.

Fried[69] showed that the vena radicularis magna has a typical coat-hook configuration in contrast to the hairpin shape of the ARM. However, other major veins of the SC do not parallel the arterial vessels. Posteriorly, there is one solitary posterior median vein (instead of the two smaller postero-lateral arteries) that is usually larger than the anterior median vein.

Several criteria can be used to identify a radicular vessel as an artery:

1. Simultaneous visualisation of ARM and ASA as two enhanced spots in the ventral aspect of the SC in consecutive transverse scans[37,47];
2. Characteristic anatomic relation of the two vessels (hairpin shape)[47];
3. Continuity of the ARM traceable to vessels of certain arterial nature (intercostal—lumbar artery, aorta)[33,37,43,47](Fig. 2);
4. Failure of enhancement and visualisation of the posterior spinal vein and of other veins surrounding the spine (intercostal, lumbar and azygos).[47]

Continuity with a vessel that is certainly an artery is clearly pathognomonic; however, because the vessels cannot always be traced, the judgement relies on other criteria that are less certain.[33,37,43,47] CT angiography performed with intra-aortic contrast media injection offered outstanding images and 100% detection of the ARM[43,45]; unfortunately, this is not standard methodology in most centres.

Boll and co-workers[40] analysed 100 scans of patients undergoing CT for pancreatic neoplasm by applying a modified brain vessel reconstruction algorithm. The ARM was visualised in all cases; unfortunately, we do not know whether this optimal detection rate was due to the improved post-processing technique or to the absence of vascular disease and the low body mass index of these patients. In a recent study,[27] the CT datasets of patients with severe aortic disease were studied using both standard radiological workstations and OsiriX software running on a regular Mac Book Pro to detect the ARM. The OsiriX analyses compared favourably with those performed using standard methods.

Multi-factorial aetiology of spinal cord ischaemia

SC ischaemia is not based exclusively on the permanent interruption of one segmental supplying the anterior spinal artery; instead, its physiopathology is multi-factorial and only partially understood. Griepp et al.[70] proposed the collateral network concept, detailing the redundancies in the blood supply to the SC. However, while the collateral network may guarantee adequate vascularisation in many instances, this is not always the case, especially in acute settings.

Thoracic endovascular aneurysm repair (TEVAR) provides an opportunity to improve our understanding of SC ischaemia aetiology because it removes the background noise of aortic cross-clamping and intercostal artery re-implantation. Kawaharada et al.[71] reported 9.1% paraplegia in patients in whom the stent graft covered the intercostal artery feeding the ARM versus 0% in the subgroup in which it did not.

Analysis of the EUROSTAR registry[72] demonstrated that SC ischaemia was correlated with the occlusion of intercostal arteries at the T10 level ($p = 0.034$, odds ratio [OR] $= 2.98$), left subclavian artery covering without revascularisation ($p = 0.023$, OR $= 3.9$), use of more than three stent grafts ($p = 0.041$, OR $= 3.4$) and simultaneous open repair of AAA and TEVAR ($p = 0.0003$, OR $= 7.96$). Previous AAA open repair has been associated with an increased risk of SC ischaemia in other studies as well.[8,73]

SC ischaemia is correlated with episodes of perioperative hypotension.[7,8] Excessive bleeding can lead to episodes of hypotension, and blood loss greater than

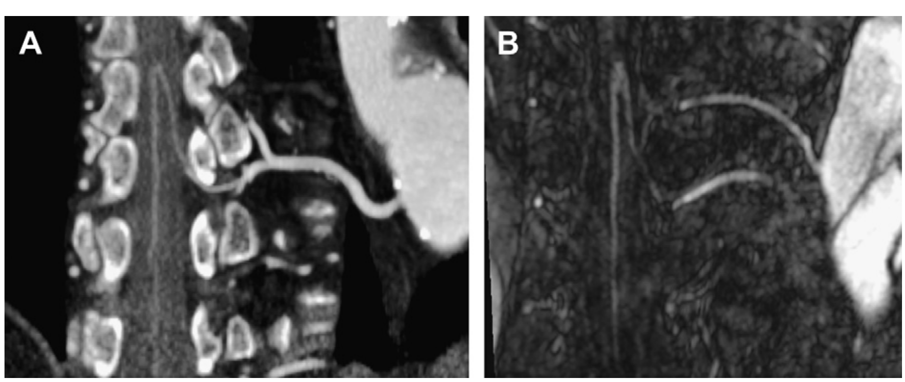

Figure 2 Non-invasive imaging of the arteria radicularis magna (ARM) using (A) computed tomography-angiography (B) magnetic resonance-angiography.

1000 ml has been demonstrated to be predictive for SC ischaemia, as has retroperitoneal haematoma combined with external iliac injury.[74] SC ischaemia is also correlated with an occluded or excluded hypogastric artery.[75] Patients who required an iliac conduit for vascular access for TEVAR developed SC ischaemia more frequently. The incidence of SC ischaemia was statistically associated with retroperitoneal approach for vascular access, and the female gender had a tendency towards increased risk of SC ischaemia, possibly because female patients were more likely to receive a retroperitoneal approach due to their small femoral vessels.[74]

Clinical relevance

The data regarding SC blood supply obtained with current non-invasive imaging modalities (Fig. 2), although extremely interesting from an academic perspective, are probably still not accurate enough to act as bases for operative strategies. Moreover, the various imaging methods only depict the vascular anatomy; they do not provide functional information. Ideally, further technological developments could address not only vascular anatomy but also information on the amount of blood that is supplied to the SC.

Once validation and improved understanding of the information acquired with MR-angiography and CT-based angiography of the SC vasculature are realised, several important clinical benefits are possible:

1. Preoperative stratification of the risk of SC ischaemia;
2. Selective intercostal/lumbar artery re-implantation (open surgery);
3. Avoidance of unnecessary coverage of intercostal feeders of the ARM (TEVAR);
4. Selective revascularisation of left subclavian artery or hypogastric artery; and
5. Selective use of adjuncts that have an intrinsic risk of complications, such as CSF drainage.

Conclusions

If the capabilities of non-invasive modalities used to image the SC blood supply in individual patients with aortic disease continue to grow at a rapid pace, it is likely that we will soon be able to define this complex vasculature preoperatively in most cases. However, questions remain about whether this information will influence the clinical approach and the outcomes, and if so, how? So far, the clinical consequences of this knowledge remain uncertain.

Based on our knowledge of normal anatomy, we know that there is always one dominant artery that feeds the anterior spinal artery in the thoraco-lumbar region (ARM); however, most studies performed in patients with TAA—TAAA disease have often failed to detect the ARM. This could be due to several different pathological or technical reasons. Vascular surgeons would benefit from knowing all of the arterial trajectories to the SC to estimate the risk of developing cord ischaemia and to act adequately when SC ischaemia occurs during surgery. Future studies will need to address the following questions:

1. In patients with thoracic aortic disease, are there differences in the SC blood supply that develop chronically and asymptomatically with the aortic disease itself? If so, are the differences relevant for the perioperative risk of SC ischaemia? Are there disease-specific differences in the SC blood supply, such as between atherosclerotic aneurysms versus dissections versus other diseases?
2. What is the post-operative fate of the ARM? Is there a correlation with the clinical outcome?
3. Is there a correlation between the presence and location of the ARM, the fate of the intercostal/lumbar feeder during the procedure (preserved, re-implanted, sutured and covered by a stent graft), and the clinical outcome?

It will be difficult to obtain all of this information for several reasons: SC vasculature varies greatly among individuals, SC ischaemia is relatively uncommon, and the aetiology of SC ischaemia is multi-factorial and differs between open and endovascular procedures. Despite these problems, even a partial reduction in the paraplegia rate is a formidable motivation for further research in this area.

Conflict of Interest

The authors report no conflicts of interest; no funding was received in support of this study.

Acknowledgements

We gratefully acknowledge Dr. Alexandre Campos Moraes Amato, Assistant Professor of Vascular Surgery, Santo Amaro University (UNISA) Medical School, Sao Paulo, Brazil, for contributions in managing the numerical data, preparing the tables, and organising the bibliography. We also thank Drs Efrem Civilini and Luca Bertoglio, Division of Vascular Surgery, Scientific Institute H. San Raffaele ''Vita-Salute'' San Raffaele University, Milan, Italy, for their help in preparing and revising the manuscript.

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