Pain Medicine

Pain Medicine 2010; 11: 1756–1764
Wiley Periodicals, Inc.

SPINE SECTION

Original Research Articles

Intraforaminal Location of the Great Anterior Radiculomedullary Artery (Artery of Adamkiewicz): A Retrospective Review

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Abstract

Purpose. The purpose of this study was to better characterize the intraforaminal location of the great anterior radiculomedullary artery (artery of Adamkiewicz [AKA]) within the neural foramen that would allow safer targeting of thoracic and lumbar transforaminal epidural steroid injections.

Material and Methods. A retrospective review of conventional thoracic and lumbar spinal angiograms performed at the Mayo Clinic from 1998–2008 was conducted. Two hundred forty-eight patients were identified and their spinal angiograms reviewed. The cephalo-caudal location of the AKA within the foramen at the mid-pedicular plane was documented along with the side and level of the AKA.

Results. From the 248 patients, 113 radiculomedullary arteries could be clearly evaluated within a neural foramen. The AKA was located in the superior one-half of the foramen in 97% (110). Eighty-eight percent (100) were located in the upper third; 9% (10) were located in the middle third; and 2% (2) were located in the lower third. The AKA was never seen in the inferior one-fifth of the foramen. Eighty-eight percent (100) of the radiculomedullary arteries were located on the left while 17% (20) were located on the right. The radiculomedullary arteries were identified from T2-L3. 92% (110) were located between T8 and L1. 28% (34) were located at T10, the highest incidence.

Conclusions. The AKA was overwhelmingly located in the superior aspect of the neural foramen. Contrary to traditional teaching, the safest needle placement for an epidural steroid injection, particularly at L3 and above, may not be in the superior aspect of the foramen, but rather in an inferior and slightly posterior position within the foramen and relative to the nerve.

Key Words. Artery of Adamkiewicz; Radiculomedullary Artery; Intraforaminal; Epidural; Transforaminal; Safe Triangle

Introduction

Transforaminal epidural steroid injections have become a common intervention in the treatment of radicular pain. The procedure involves an image-guided needle placement, contrast injection to exclude intravascular or intrathecal communication and assess epidural spread pattern, with subsequent local anesthetic and corticosteroid injection about the pre and post ganglionic nerve [1–3]. Several studies and systematic reviews have demonstrated the efficacy of the procedure [4–14]. Complications, though rare, can be catastrophic. To our knowledge, 12 case reports have described acute paraplegia/spinal cord infarction despite conventionally accepted image-guided procedural techniques for transforaminal epidural steroid injections in the thoracic and lumbar spine [1,15–21].

Typically, the needle tip is placed under image guidance into the superior aspect of the neural foramen, just caudal to the six o'clock position of the superior pedicle, in the so-called "safe triangle" [3,22,23] (Figure 1). This places the needle immediately superior and lateral to the exiting nerve, allowing access to the ventral epidural space while avoiding potential traumatic injury to the nerve. While this may be relatively safe in the lower lumbar spine (L4 and L5), in the upper lumbar spine and in the thoracic spine this location within the upper foramen may contain the great anterior radiculomedullary artery (Artery of Adamkiewicz [AKA]) (Figure 2).

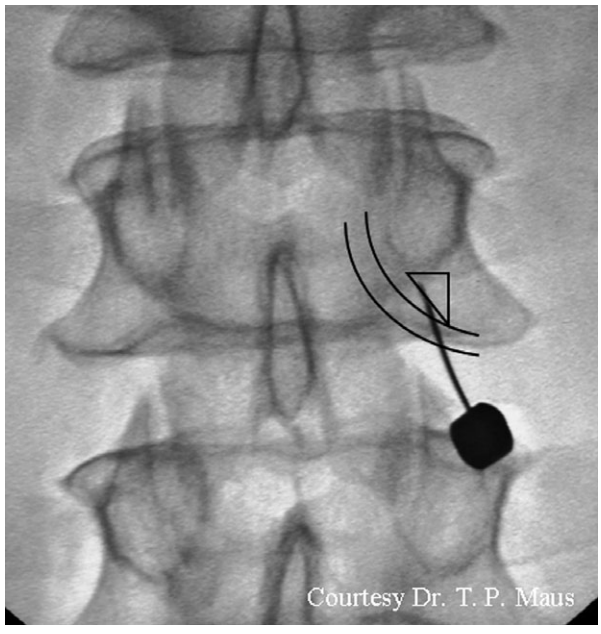

Figure 1 Fluoroscopic anterior-posterior image of a right lumbar epidural injection with the needle placed in the "safe triangle." The curved black lines represent the normal course of the exiting nerve.

The AKA is the largest intradural blood supply to the anterior spinal cord. The AKA arises from the medial trunk of the intercostal or lumbar segmental arteries in the thoracic and lumbar spine. It enters the spinal canal in immediate proximity to the exiting spinal nerve, typically situated ventral or slightly rostrolateral to the dorsal root ganglion/ventral ramus [24]. The AKA then takes a rostral turn along the nerve root where it eventually joins the anterior spinal artery in a classic hairpin configuration [24] (Figure 2). The average diameter of the AKA at the dorsal root ganglion and foramen was 1.84 and 1.53 mm, respectively, in the study of Allenyne, and 1.12 $\pm$ 0.23 mm in that of Biglioli.

The AKA has been shown to arise from left-sided intercostal or lumbar arteries in 67.7% of patients in one anatomic study [25] and in 78% in another [24]. Its vertebral level of origin cannot be predicted in the individual patient; 83.9% have been shown to arise from T12 to L3 [25]; 85% have been shown to arise from T9 to L2 [24].

Catastrophic neurological injury during transforaminal epidural steroid injection is postulated to have occurred by occlusion of the AKA, either by direct intimal needle injury with thrombosis, induced arterial vasospasm, or arterial embolization with particulate steroids [1,15–21]. The precise anatomy of the AKA within the neural foramen has not been well described in large populations, but would be very relevant to avoiding such catastrophic injuries. To our knowledge, no retrospective review of conventional (catheter) thoracic and lumbar spinal angiograms has been performed to evaluate the intraforaminal location of the AKA. By better characterizing the location of the AKA within the neural foramen, we hope to achieve safer targeting of transforaminal epidural steroid injections, particularly in the upper lumbar and thoracic spine.

Materials and Methods

The research protocol used was reviewed and approved by the Mayo Institutional Review Board. A retrospective review was performed of all subjects who had undergone conventional spinal angiography (digital subtraction or manual subtraction) of the thoracic and lumbar spine at the Mayo Clinic Rochester from 1998–2008. The electronic medical record was queried for identification of "Artery of Adamkiewicz" in the radiologists' angiography reports. Only those patients who had consented to research authorization were included in the study cohort, and their medical records, including images, were then reviewed.

Those subjects included in the study had their angiogram images and reports specifically reviewed for the side and vertebral level of the AKA. Most of the angiograms were monoplane and were performed to evaluate for a possible arteriovenous malformation or a dural arteriovenous fistula. Examinations prior to 2003 typically began with a low abdominal aortic flush injection to detect low lumbar contributions to the spinal cord, with subsequent selective lumbar and intercostal artery injections. Post 2003 angiograms were often more selective, based on magnetic resonance angiographic images; this could bias against detection of low lumbar AKAs. The angiogram images were reviewed to identify the intraforaminal location of the AKA on frontal projections as it passed through the midpedicular plane bounded by the superior and inferior pedicle. A ratio was calculated of the distance from the inferior margin of the superior pedicle to the center of the AKA divided by the entire cephalo-caudal dimension of the foramen. This foraminal ratio allowed categorization of the relative cephalo-caudal location of the AKA within the neural foramen independent of magnification and patient size (Figure 3). All the results were tabulated and descriptive statistics were generated for the vertebral level, side, and relative position within the neural foramen.

Results

Based upon the inclusion criteria set forth, 248 patients were identified. Of these 248 patients, 120 radiculomedullary arteries could be identified in 115 patients. Three patients had two radiculomedullary arteries contributing to the anterior spinal artery. One patient had three radiculomedullary arteries, all occurred at different levels and one on the contralateral side.

Of these 120 radiculomedullary arteries, 83% (100) were located on the left, and 17% (20) were located on the right. All the radiculomedullary arteries were located

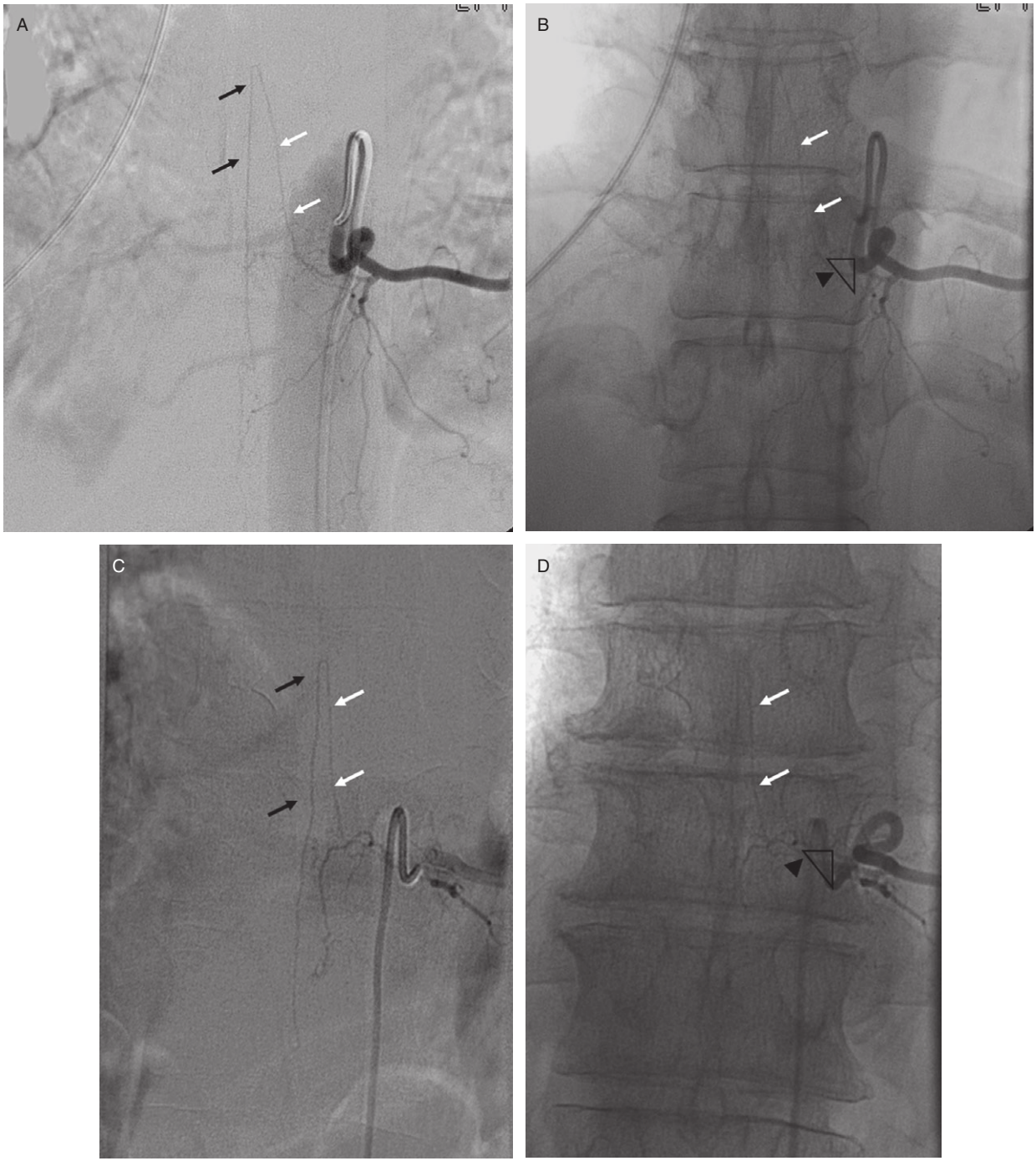

Figure 2 (A) and (C), selected digital subtraction angiograms of a left intercostal artery. Classic hairpin appearance of the great anterior radiculomedullary artery (AKA) (white arrows) joining the anterior spinal artery (black arrows). (B) and (D), same images as (A) and (C) without subtraction showing the osseous landmarks and the location of the "safe triangle," including its relation to the great anterior radiculomedullary artery (AKA) (white arrows). Note that the AKA passes through the "safe triangle" in the upper third of the foramen at the six o'clock position of the superior pedicle (black arrowhead). Artery of Adamkiewicz = AKA.

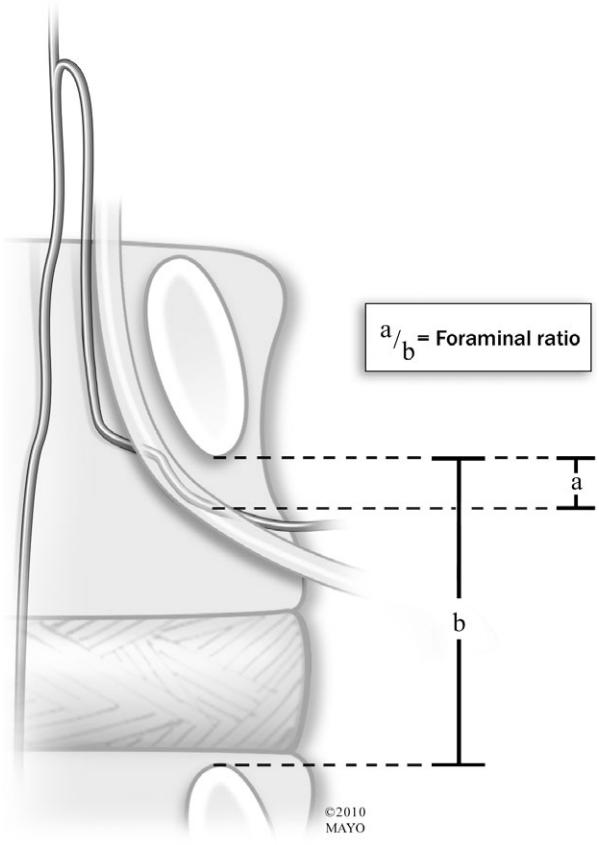

Figure 3 To provide a fluoroscopically observable classification, the neural foramen was divided into equal thirds spanning from the inferior margin of the superior pedicle to the superior margin of the inferior pedicle. A ratio was calculated of the distance from the inferior margin of the superior pedicle to the center of the AKA divided by the entire cephalo-caudal dimension of the foramen (pedicle margin to pedicle margin) along the mid-pedicular plane. This foraminal ratio allowed categorization of the relative cephalo-caudal location of the AKA within the neural foramen independent of magnification and patient size. Artery of Adamkiewicz = AKA.

between T2 and L3, with 92% (110) located between T8 and L1. The highest incidence was at T10, where 28% (34) were identified.

Among these 120 radiculomedullary arteries, the position within the foramen could not be accurately assessed in seven, due to a combination of factors, including obscuration by spinal instrumentation, poor visualization, and obliquity. The distribution of the intraforaminal locations of the remaining radiculomedullary arteries, as determined at the mid-pedicular plane, is graphically depicted using the foraminal ratio, in 0.10 increments (Figure 4). The AKA was located in the upper one half of the foramen 97% of the time (110/113); 88% (100) were located in the upper third of the foramen (1 was located at the junction of the upper and middle third); 9% (10) were located in the middle third of the foramen; 2% (2) were located in the lower third of the foramen. The AKA was never seen in the most inferior one fifth of the foramen.

Discussion

Among the 12 case reports of acute paraplegia/spinal cord infarction following a transforaminal epidural steroid injection in the thoracic or lumbar region, the postulated etiologies for these events included compromise of the AKA by direct needle injury and thrombosis, induced arterial vasospasm, and arterial embolization with particulate steroids. The precise mechanism is unknown. All cases involved the use of particulate steroids. There was a preponderance of post operative cases (7/12). One case occurred at T12, one at L1, two at L2, five at L3 (including one case with simultaneous L3 and L4 injections), two at L5, and one at S1. Eight of the 12 cases involved left-sided injections. No lumbar side or level was immune, but there was a clear predilection for the left upper lumbar region, mirroring the distribution of the AKA. Although our

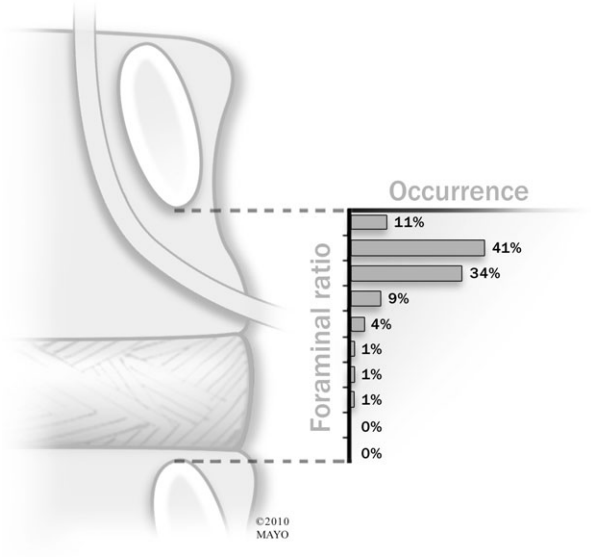

Figure 4 Distribution of the intraforaminal locations of the remaining 113 radiculomedullary arteries, as determined at the mid-pedicular plane, is graphically depicted using the foraminal ratio, in 0.10 increments. The artery of Adamkiewicz was located in the upper one-half of the foramen 97% of the time (110/113) and was never seen in the most inferior one-fifth of the foramen.

series did not detect any examples of the AKA and/or other radiculomedullary arteries below the L3 level, this has been previously reported. Biglioli's autopsy series of 51 cadavers noted the AKA to be below T12 in 70.5% of cases, between L1 and L3 in 64.7% of cases, and below L2 in 23.5%. One left-sided AKA was seen at L4 and two left-sided AKAs detected at L5. Lo et al. [26] described 3 cases of L4 AKAs in an angiographic series of 4000.

In nine of these case reports [1,15,17–21], there was a comment and/or published images indicating placement of the needle close to the spinal nerve as it exited the upper third of the neural foramen, i.e., within the conventionally instructed "safe triangle" [3,22,23]. All of the reported cases of acute paraplegia/spinal cord infarction occurred after 2000, which is 5 years after the publication of the "safe triangle" approach [3,22,23]. This "safe triangle" approach was intended to avoid the spinal nerve while allowing the needle to pass to the ventral epidural space, closer to the presumed locus of pain generation in radicular pain syndromes. At the time of its description, catastrophic neurologic injury due to an encounter with the AKA had not been reported. Unfortunately, proximity to the targeted nerve within the superior neural foramen also brings with it proximity to the AKA. In our series, 97% of the AKAs were in the upper half of the foramen as they passed the mid-pedicular plane under the pedicle. Only 2% were seen in the lower one-third of the foramen, and the AKA was never seen in the most caudal one-fifth of the foramen.

An infraneural approach to transforaminal epidurals, targeting the lower portion of the foramen and remaining posterior to the exiting nerve, should diminish the likelihood of needle contact with the AKA and vascular insult to the cord, whether due to embolization, vasospasm, or thrombosis. It remains prudent to employ all other known strategies to reduce the risk of cord injury. Particulate steroids are a common denominator to all previously reported spinal cord injuries from lumbar transforaminal injections; use of nonparticulate steroid preparations (dexamethasone sodium phosphate) may be prudent, especially in the upper lumbar region (L3 and above). The relative efficacy of dexamethasone vs particulate steroids remains in question. Meticulous contrast injection to exclude vascular filling remains obligatory. It is well established that negative aspiration does not exclude vascular penetration [27]. Digital subtraction imaging during contrast injection improves the likelihood of detection of vascular opacification [28]. Local anesthetic test injections prior to steroid administration may also add safety, although based on a single observation [29]. The dominance of postoperative cases suggests they may hold unique risks; Wybier postulates the potential development of arterial communications between granulation tissue and a radiculomedullary artery. Injection into a foramen bearing epidural fibrosis should perhaps only be done with nonparticulate steroid.

One limitation of our study is that it includes only a two-dimensional analysis of the AKA with respect to the neural foramen. Our investigation was limited to posterior–anterior angiographic projections, as lateral angiographic projections were sometimes but not usually available. The two-dimensional data suggest that needle placement in the most caudal portion of the foramen would greatly reduce the chances of encountering the AKA, even though we were not typically able to assess its ventral–dorsal position within the foramen. Cadaveric studies have shown that the AKA typically enters the spinal canal ventral or slightly rostrolateral to the dorsal root ganglion/ventral ramus [20,21,24]. By staying posterior to the spinal nerve, this would also reduce potential encounters with the AKA. This would further support an inferior and posterior position within the foramen relative to the nerve. As the post-ganglionic nerve is progressing anteriorly exiting the foramen, a needle can closely approach the ventral epidural space in the inferior foramen while still remaining posterior to the nerve. The nerve effectively shields the needle tip from the artery.

This infraneural approach, and its potentially greater margin of safety, has been previously described [1,30]. Windsor and Falco suggested placement of transforaminal needles in the inferior aspect of the foramen as a means of reducing risk of vascular injury in 2001 [30]; Glaser and Falco elaborated further on this targeting in 2005 [1]. They noted that an inferior approach provides greater safety and better delivery of injectate into the ventral epidural space than the classic "safe triangle" targeting, but requires care to avoid disc puncture, as it is essentially a discographic needle path (Figure 5a). While disc puncture carries a theoretical risk of infection, removing the risk of paraplegia dominates the risk—benefit judgment. In a subsequent publication, Glaser and Shah [31] advocate strongly for an inferior foraminal approach as a safer means of performing transforaminal injections; they also echo the comments of Jasper [32] that this approach directly targets the purported pain generator, the disc—nerve interface. Jasper describes infraneural targeting as a retrodiscal approach, and also notes that injected contrast usually spreads into the ventral epidural space, caudal about the traversing nerve, and cephalad about the exiting nerve, as has been our observation [32]. There have been no quantitative studies of epidural spread patterns using this approach, nor efficacy studies comparing the classic supraneural approach vs the infraneural targeting we described. Lee and colleagues [33] found no difference in short-term (2 weeks) pain relief in transforaminal epidurals for needle placement in the ventral epidural space via the classic supraneural approach vs injections immediately posterior to the nerve. Their retroneural targeting does not appear to have been as inferior or anterior in the foramen as we suggested.

Our current practice for transforaminal epidural steroid injections at L3 and above consists of an inferior and slightly posterior approach to the nerve within the foramen (Figures 5 & 6). The inferior aspect of the neural foramen is targeted using an ipsilateral oblique approach, much like a discogram. This provides a direct trajectory for the needle along the X-ray beam which passes just lateral to the

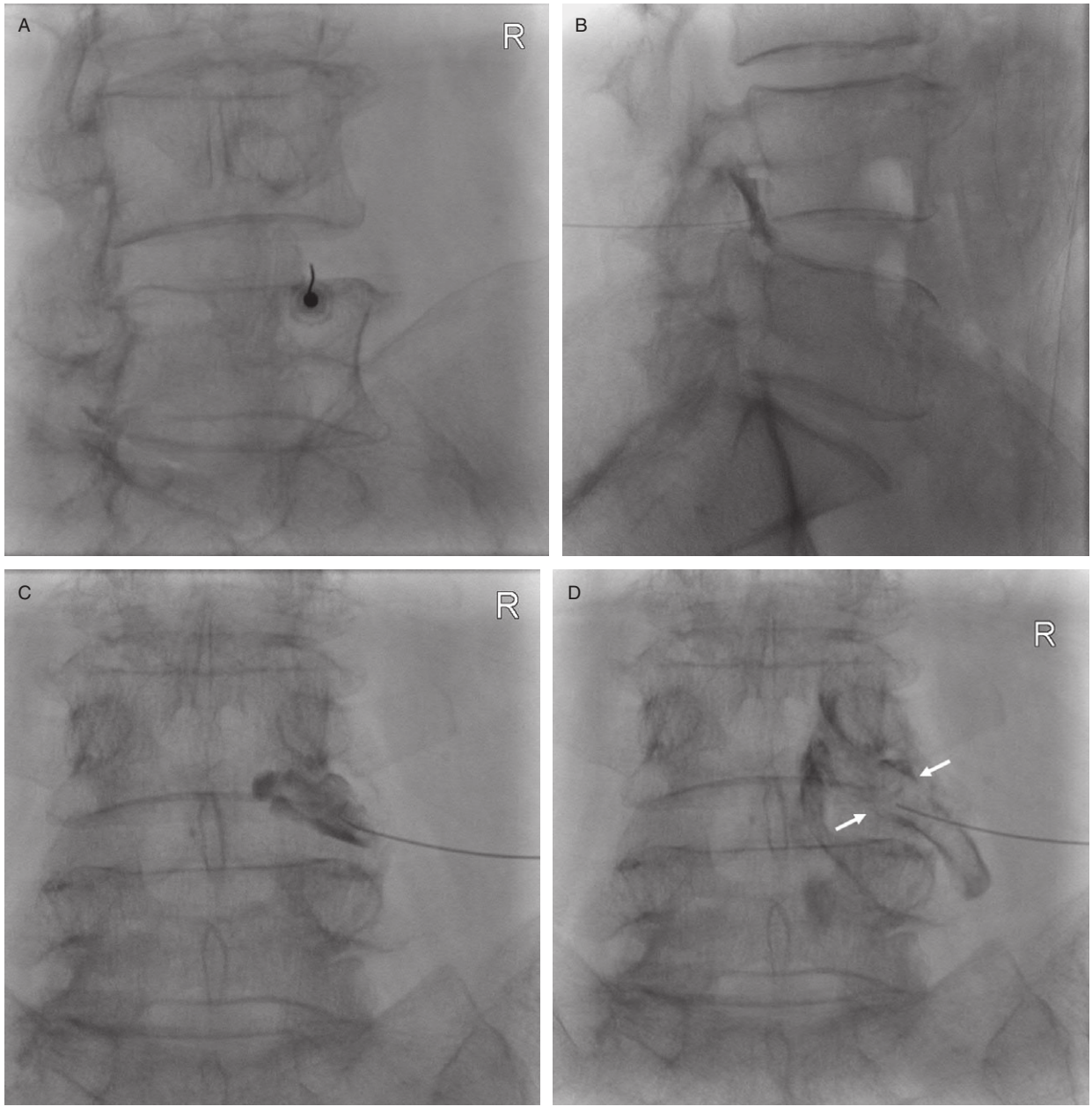

Figure 5 New proposed transforaminal epidural injection approach at L3 and above. Ipsilateral oblique approach for needle placement in the inferior and slightly posterior aspect of the neural foramen and nerve (A). Test contrast injection demonstrating pure central and peripheral epidural flow outlining the dorsal root ganglion and post-ganglionic nerve (white arrows) (B, C, and D).

superior articular process of the facet joint into the foramen. A position no more medial than the six o'clock position of the superior pedicle, as evaluated in the posteroanterior plane, is targeted. The lateral projection is used to assess the depth of the needle for its final advancement to a position just posterior to the expected location of the nerve, based on inspection of pre procedure computed tomography or magnetic resonance imaging (MRI) scans. Care must be taken to avoid disc penetration; comparison of sagittal MRI images with the live fluoroscopic image is very helpful. A test contrast injection is made to confirm the needle's epidural and extravascular position in both lateral and anterior-posterior planes, including an AP digital subtraction run if there is any question regarding vascular opacification. In our experience, an infraneural needle placement can provide excellent flow

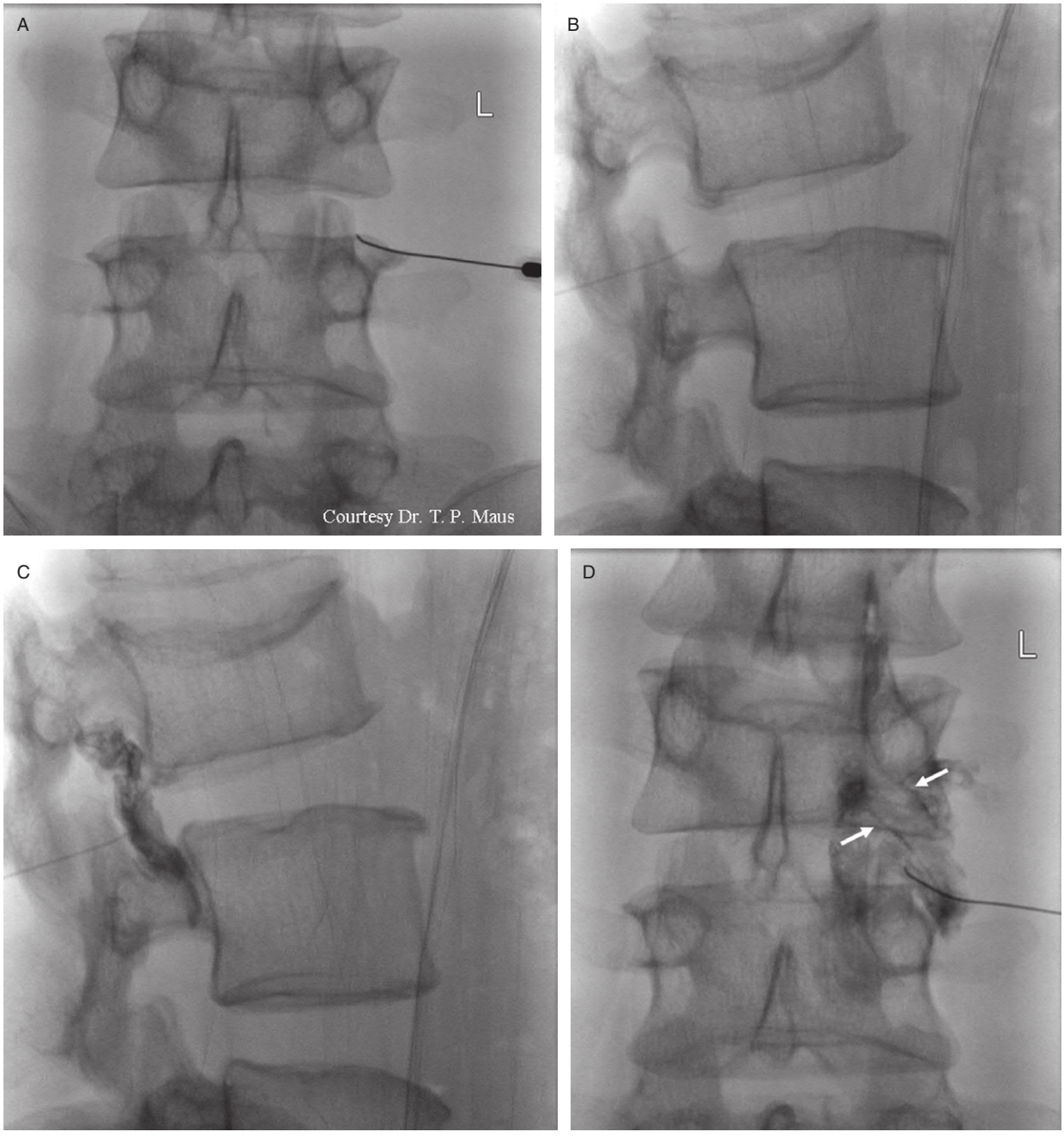

Figure 6 Another example of the new proposed transforaminal epidural injection approach at L3 and above. Needle placement in the inferior and slightly posterior aspect of the neural foramen and nerve (A and B). Test contrast injection demonstrating pure central and peripheral epidural flow outlining the dorsal root ganglion and post-ganglionic nerve (white arrows) (C and D).

into the ventral epidural space, surrounding the traversing and exiting roots. As noted by Glaser and Falco, there is less dominant cephalad flow of contrast. Documentary images are obtained prior to and following contrast injection in both anterior-posterior and lateral planes, as well as a washout image. A test injection of 1 cc of preservative-free 2% lidocaine is then performed to assess for potential central neurologic deficits from an unrecognized intra-

vascular injection. A 1–2 minute pause is performed to allow for the onset of action of lidocaine, after which the patient is asked to demonstrate normal lower extremity movement. Dexamethasone sodium phosphate (10 mg/mL) is then used to further diminish any risk of arterial embolization. Although we have mandated this protocol for all upper lumber and thoracic injections, the potential for encounters with the AKA within lower lumbar foramina exists, and use of an infraneural approach and nonparticulate steroid for all lumbar injections would be reasonable, and is encouraged in our practice.

Conclusion

The great anterior radiculomedullary AKA is generally found in the superior aspect of the neural foramen; 97% of occurrences are in the upper half of the foramen. Based upon this data, we propose that the safest needle placement for an epidural injection, particularly at L3 and above, may not be in the superior aspect of the foramen, contrary to traditional teaching. We would suggest that an infraneural approach, with the needle placed in the inferior foramen, remaining posterior to the exiting nerve but approaching the ventral epidural space, may best avoid the AKA and minimize the likelihood of catastrophic vascular complications of transforaminal epidural injections.

Acknowledgments

We would like to thank Mrs. Jane Gagnon for the preparation of this manuscript.

Financial Disclosure

The authors have nothing to disclose.

References

1 Glaser SE, Falco F. Paraplegia following a thoracolumbar transforaminal epidural steroid injection. Pain Physician 2005;8(3):309–14.

2 Sitzman BT. Epidural injection. In: Fenton DS, Czervionke LF, eds. Image-Guided Spine Intervention. Philadelphia: Saunders Publishing; 2003:99–126.

3 Bogduk N. An algorithm for the investigation of low back pain. In: Bogduk N, ed. Practice Guidelines for Spinal Diagnostic and Treatment Procedures. San Francisco, CA: International Spine Intervention Society; 2004:86–94.

4 Boswell MV, Hansen HC, Trescot AM, Hirsch JA. Epidural steroids in the management of chronic spinal pain and radiculopathy. Pain Physician 2003;6(3):319–34.

5 Abdi S, Datta S, Lucas LF. Role of epidural steroids in the management of chronic spinal pain: A systemic review of effectiveness and complications. Pain Physician 2005;8(1):127–43.

6 Abdi S, Datta S, Trescot AM, et al. Epidural steroids in the management of chronic spinal pain: A systematic review. Pain Physician 2007;10(1):185–212.

7 Karppinen J, Malmivaara A, Kurunlahti M, et al. Periradicular infiltration for sciatica: A randomized controlled trial. Spine 2001;26(9):1059–67.

8 Karppinen J, Ohinmaa A, Malmivaara A, et al. Cost effectiveness of periradicular infiltration for sciatica: Subgroup analysis of a randomized controlled trial. Spine 2001;26(23):2587–95.

9 Roberts ST, Willick SE, Rho ME, Rittenberg JD. Efficacy of lumbosacral transforaminal epidural steroid injections: A systematic review. PM R 2009;1(7):657–68.

10 Buenaventura RM, Datta S, Abdi S, Smith HS. Systematic review of therapeutic lumbar transforaminal epidural steroid injections. Pain Physician 2009;12(1):233–51.

11 Vad VB, Bhat AL, Lutz GE, Cammisa F. Transforaminal epidural steroid injections in lumbosacral radiculopathy: A prospective randomized study. Spine 2002;27(1):11–6.

12 Riew KD, Yin Y, Gilula L, et al. The effect of nerve root injections on the need for operative treatment of lumbar radicular pain. A prospective, randomized, controlled, double-blind study. J Bone Joint Surg Am 2000;82-A(11):1589–93.

13 Riew KD, Park JB, Cho YS, et al. Nerve root blocks in the treatment of lumbar radicular pain. A minimum 5-year follow-up. J Bone Joint Surg Am 2006;88(8):1722–5.

14 Thomas E, Cyteval C, Abiad L, et al. Efficacy of transforaminal vs interspinous corticosteroid injection in discal radiculalgia—a prospective, randomized, double-blind study. Clin Rheumatol 2003;22(4–5):299–304.

15 Houten JK, Errico TJ. Paraplegia after lumbosacral nerve root block: Report of three cases. Spine J 2002;2(1):70–5.

16 Huntoon MA, Martin DP. Paralysis after transforaminal epidural injection and previous spinal surgery. Reg Anesth Pain Med 2004;29(5):494–5.

17 Kennedy DJ, Dreyfuss P, Aprill CN, Bogduk N. Paraplegia following image-guided transforaminal lumbar spine epidural steroid injection: Two case reports. Pain Med 2009;10(8):1389–94.

18 Lyders EM, Morris PP. A case of spinal cord infarction following lumbar transforaminal epidural steroid injec-

tion: MR imaging and angiographic findings. Am J Neuroradiol 2009;30(9):1691–3.

19 Somayaji HS, Saifuddin A, Casey AT, Briggs TW. Spinal cord infarction following therapeutic computed tomography-guided left L2 nerve root injection. Spine 2005;30(4):E106–8.

20 Wybier M. Transforaminal epidural corticosteroid injections and spinal cord infarction. Joint Bone Spine 2008;75(5):523–5.

21 Wybier M, Gaudart S, Petrover D, Houdart E, Laredo JD. Paraplegia complicating selective steroid injections of the lumbar spine. Report of five cases and review of the literature. Eur Radiol 2010;20(1):181–9.

22 Bogduk N, Aprill C, Derby R. Selective nerve root blocks. In: Wilson DJ, ed. Practical Interventional Radiology of the Musculoskeletal System. London: Arnold Publishing; 1995:122–32.

23 Bogduk N, Aprill C, Derby R. Epidural steroid injections. In: White AH, Schofferman J, eds. Spinal Care Diagnosis and Treatment. St. Louis: Mosby; 1995: 322–43.

24 Allenyne CH Jr, Cawley CM, Shengelaia GG, Barrow DL. Microsurgical anatomy of the artery of Adamkiewicz and its segmental artery. J Neurosurg 1998;89(5):791–5.

25 Biglioli P, Spirito R, Roberto M, et al. The anterior spinal artery: The main arterial supply of the human spinal cord-a preliminary anatomic study. J Thorac Cardiovasc Surg 2000;119(2):376–9.

26 Lo D, Valleé JN, Spelle K, et al. Unusual origin of the artery of Adamkiewicz from the fourth lumbar artery. Neuroradiology 2002;44(2):153–7.

27 Furman MB, O'Brien EM, Zgleszewski TM. Incidence of intravascular penetration in transforaminal lumbosacral epidural steroid injections. Spine 2000; 25(20):2628–32.

28 McLean JP, Sigler JD, Plastaras CT, et al. The rate of detection of intravascular injection in the cervical transforaminal epidural steroid injections with and without digital subtraction angiography. Phys Med Rehabil 2009;1(7):636–42.

29 Baker R, Dreyfuss P, Mercer S, Bogduk N. Cervical transforaminal injection of corticosteroids into a radicular artery: A possible mechanism for spinal cord injury. Pain 2003;103(1–2):211–5.

30 Windsor RE, Falco FJE. Paraplegia following selective nerve root blocks. ISIS Sci Newsl 2001;4: 53–4.

31 Glaser SE, Shah RV. Root cause analysis of paraplegia following transforaminal epidural steroid injections: The "unsafe" triangle. Pain Physician 2010;13(3):237–44.

32 Jasper JF. Lumbar retrodiscal transforaminal injection. Pain Physician 2007;10(3):501–10.

33 Lee IS, Kim SH, Lee JW, et al. Comparison of the temporary diagnostic relief of transforaminal epidural steroid injection approaches: Conventional vs posterolateral technique. Am J Neuroradiol 2007;28(2): 204–8.