CT Angiography in Pediatric Extremity Trauma: Preoperative Evaluation Prior to Reconstructive Surgery

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Received: 11 May 2007 / Accepted: 19 October 2007 / Published online: 7 November 2007
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Abstract Computed tomographic angiography (CTA) is a noninvasive modality for evaluating the vascular system and planning treatment strategies. The goal of this study was to validate the clinical utility of CTA in assessment of suspected pediatric extremity traumatic vascular injury, prior to emergent and delayed reconstructive surgery. A retrospective review was performed of all operative patients under 18 years of age who underwent multidetector-row CTA for evaluation of suspected extremity vascular injury. Parameters investigated included age, type of injury, referral source, temporal relationship between the injury and the CTA, CTA findings, operations performed, intraoperative findings, and clinical outcome. Between January 2002 and September 2005, 10 pediatric patients (6 males/4 females; mean age 8 years old, range 3–17) sustained either blunt ($N=8$) or penetrating ($N=2$) trauma and underwent CTA of the upper ($N=5$) or lower extremities ($N=5$). A total of 30% (3/10) of patients were referred from the emergency department acutely, 50% (5/10) were referred from the inpatient wards subacutely, and 20% (2/10) were referred from the outpatient clinics electively. Half ($N=5$) underwent CTA to evaluate need for vascular repair, whereas half ($N=5$) underwent CTA to evaluate local vasculature for flap reconstruction. Overall, 40% (4/10) of CTA findings were

normal, whereas 60% (6/10) revealed traumatic vascular injuries. Pertinent nonvascular findings included soft tissue defects (60%, 6/10), fractures (40%, 4/10), and contracture deformities (20%, 2/10). In all cases, procedures were completed without complications, and intraoperative findings confirmed those from CTA. At a mean follow-up of 28 months, all injuries have healed without complications. CTA is a reliable noninvasive modality to evaluate pediatric patients with suspected traumatic extremity vascular injury and to plan treatment strategies for both vascular repair and extremity reconstruction.

Keywords Computed tomographic angiography · Clinical utility · Pediatric extremity traumatic vascular injury

Introduction

Conventional catheter angiography is considered the gold standard for evaluation of the cardiovascular system. Over the past 15 years, computed tomographic angiography (CTA) has emerged as an alternative noninvasive modality with many clinical applications [18]. In pediatric patients, CTA is utilized for evaluation of a number of problems: cerebral aneurysms [17, 23], cerebral neoplasms [1], craniofacial anomalies [25], oropharyngeal trauma [4], vascular compressive syndromes of the airway [2], esophageal and gastric varices related to portal hypertension [13], liver transplantation [6], small bowel transplantation [20], renal disease [19], congenital heart disease [11], Takayasu's arteritis [21], vascular stent complications [9], thoracic outlet syndrome [24], great vessel anomalies [14], and other intrathoracic vascular pathology [5, 8, 26, 27].

CTA has also been reported in evaluation of suspected extremity traumatic vascular injury [3]. There are several

No financial relationships to close.

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key reasons to implement CTA in this clinical algorithm, particularly with pediatric patients. First, catheter angiography is an invasive procedure that can lead to both minor and major complications, including dissection, pseudoaneurysm, hemorrhage, hematoma, thromboembolism, vasospasm, and end-organ ischemia. Risks may pose a greater threat in the pediatric population, given the smaller vessel diameter. Studies examining the safety of pediatric femoral artery access for angiography report vasospasm in 62% [10], transient pulse loss in 6% [28], hematoma in 5% [28], and occasional long-term arterial occlusion [28]. CTA eliminates the need for femoral artery catheterization and, as such, these potential risks. Second, CTA can provide vascular imaging of the extremity for some pediatric patients in whom conventional angiography is impossible. Third, with its superior spatial resolution, CTA allows not only vessel lumen but also vessel wall and nonvascular anatomical evaluations. Fourth, whereas catheter angiography is a projectional technique, CT angiograms are volumetric. The data sets can be viewed three-dimensionally in multiple planes and projections. Fifth, CT scanners have greater clinical accessibility with fast patient throughput, have close proximity to an emergency department, and have rapid image acquisitions with short exam times.

Since 2002, our institution has used CTA to evaluate pediatric extremity vasculature in the setting of trauma prior to soft tissue reconstruction. The purpose of this study is to retrospectively review our experience to date and examine the clinical utility of CTA for evaluation of suspected pediatric extremity vascular trauma. We hypothesize that CTA would be useful in accurately assessing these injuries and guiding operative treatment.

Materials and Methods

Study Population

Retrospective review was undertaken of all pediatric patients between January 2002 and September 2005 requiring microvascular surgery who also underwent multi-detector-row CT (MDCT) angiography. Subsequent inclusion criteria were (1) age less than 18 years and (2) injury involving the upper or lower extremity that necessitated surgery. Evaluation was performed under a protocol approved by our institutional review board. The study conformed to guidelines adhering to the Health Insurance Portability and Accountability Act.

Retrospective review identified 10 patients (6 males, 4 females). All patients had normal renal function and no history of allergies to iodinated contrast material. Clinical history was obtained and operations were performed by a single plastic surgeon with microsurgical expertise (JC).

CTA Technique

Exams were performed on either 8- ($N=2$) or 16- ($N=8$) channel MDCT scanners. Eight-channel exams were acquired on a Light-Speed Ultra scanner (GE Medical Systems, Milwaukee, WI, USA), whereas 16-channel exams were acquired on either a Light-Speed 16 scanner ($N=4$, GE Medical Systems) or a Somatom 16 scanner ($N=4$, Siemens Medical Solutions, Forchheim, Germany). Patients were positioned supine on the CT gantry tables. For the upper-extremity exams, the affected extremity was either raised and abducted above the patient's head ($N=3$) or placed at the patient's side ($N=2$). Lower-extremity CT angiograms were acquired with the affected extremity isocenter on the gantry table. Tape was utilized to secure the hand or foot for upper- or lower-extremity exams, respectively. In all scans, coverage began at least one vascular segment above the region of injury and extended through to the digits. For an upper-extremity exam, this entailed beginning at either the shoulder ($N=3$) or the lower upper arm ($N=2$), whereas for the lower-extremity exams, coverage began either at the mid thigh ($N=3$) or hip ($N=2$).

Intravenous (IV) access was achieved in the antecubital fossa of an upper extremity using a 20–22-g IV catheter. For the upper-extremity CT angiograms, IV access was placed in the contralateral antecubital fossa. Nonionic contrast (Iohexol [Omnipaque 300]; GE Healthcare, Princeton, NJ, USA) was administered via a power injector (Empower CTA, E-Z-EM, Westbury, NY, USA) at 2–4 cm³/s. Scans were triggered using monitoring software to identify a rise of 100 Hu in the vascular segment above the level of injury. When using the eight-channel Light-Speed Ultra scanner, parameters were the following: 1.25 mm collimation, 1.35 pitch, 0.5 s gantry rotation time. With a mean coverage of 418 mm for this scanner, the mean scan duration was 15.5 s. Images were reconstructed at a nominal section thickness of 1.25 mm at 0.8-mm increments. Using the 16-channel Light-Speed scanner, parameters included a collimation of 0.625–1.25 mm, a pitch of 0.9375–1.375, and a gantry rotation time of 0.6 s. With a mean scan coverage of 506 mm, the mean scan duration was 15 s. Images were reconstructed with a 0.625–1.25-mm nominal section thickness at 0.625–0.8-mm increments. For the Somatom 16-channel scanner, the mean scan coverage was 608 mm. With a collimation of 0.75, a pitch of 1, and a gantry time of 0.5 s, this resulted in a mean scan duration of 25 s. Images were reconstructed at a nominal section thickness of 1–2 mm every 0.5–1 mm. The x-ray tube potential was either 80 or 120 kVp, whereas the tube current ranged between 200 and 400 mA.

All exams were transferred to a thin client workstation (TeraRecon, San Mateo, CA, USA) for image display and interpretation. Images were primarily interpreted by two experienced cardiovascular radiologists (JH, GR) using a

combination of volume rendered, maximum intensity projection, multiplanar reformation, and curved planar reformation visualization techniques. Pertinent three-dimensional images were archived and later accessed during surgical interventions.

Analysis

Analysis was performed in consensus by a cardiovascular radiologist (JH) and two plastic and reconstructive surgeons (CH, JC). Parameters reviewed included patient age, type and site of injury, referral source, timing of CTA in relation to time of injury, findings on CTA, operation(s) performed, intraoperative findings, and clinical outcome. The time between the injury and the CTA acquisition was defined as acute (<24 h after injury), subacute (1–7 days after injury), or elective (>7 days after injury). Clinical outcome was defined by at least 4 months of follow-up.

Results

Ten pediatric trauma patients ranging from 3 to 17 years of age (mean 8 years of age) underwent CTA prior to reconstructive surgery (Table 1). CTA was performed acutely in 30% (3/10). The remainder were performed on either a subacute (50%, 5/10) or elective (20%, 2/10) basis. Acute studies were referred from the emergency department, subacute patients were from the inpatient wards, and elective cases were referred from the outpatient clinics. Affected extremities included five upper (four right/one left) and five lower (two right/three left) limbs. The level of injuries in the upper extremity included the elbow ($N=2$), forearm ($N=2$), or distal upper arm ($N=1$), whereas the level of injuries in the lower extremity included the calf ($N=4$) or foot ($N=1$). The mechanism of injury included degloving injuries (30%, 3/10), supracondylar fractures (30%, 3/10), crush injuries (20%, 2/10), and penetrating trauma (20%, 2/10).

Indications for CTA included (1) suspected vascular injury based on zone of injury or distal ischemia and (2) preoperative evaluation prior to microsurgical flap reconstruction. Indications were evenly divided: 50% (5/10) had CTA performed for the purpose of evaluating suspected vascular injury that might require operative repair, whereas the other 50% (5/10) had CTA performed to evaluate vasculature prior to flap reconstruction. Overall, 60% (6/10) revealed traumatic vascular injuries on CTA, whereas 40% (4/10) had normal CTA findings. Pertinent nonvascular findings included soft tissue defects (60%, 6/10), acute and subacute fractures (40%, 4/10), and contracture deformities (20%, 2/10).

Reconstructive surgery for each patient was based upon CTA findings and included vascular repair or flap coverage.

There were no immediate or delayed procedural complications, and intraoperative findings corroborated CTA interpretations in all cases. At a mean follow-up of 28 months (range 5–49 months), vascular and soft-tissue injuries have healed without delayed vascular diagnoses.

Case Presentations

Case 1: Patient 1, preoperative evaluation of recipient vessels prior to microsurgical flap transfer

A 17-year-old female sustained a right-forearm degloving injury. Physical examination revealed exposed bone and diminished distal pulses, raising the suspicion for vascular injury (Fig. 1). CTA demonstrated normal, intact vasculature with a large soft-tissue defect and no fracture. The patient underwent coverage with a free rectus muscle flap and skin graft. After 49 months of follow-up, the patient is doing well with intact distal perfusion and durable coverage of her wound.

Case 2: Patient 2, acute evaluation of upper extremity penetrating injury with hand ischemia

A 16-year-old male suffered a stab wound to the right proximal forearm. Physical examination was remarkable for an open wound in the forearm, extending to the antecubital fossa (Fig. 2). Distal pulses were diminished, and the hand was pale. CTA revealed a transected brachial artery with absent flow in the proximal radial and ulnar arteries. Remaining blood flow to the hand was via the ulnar collateral network at the elbow into the ulnar and interosseous arteries, with small muscular collaterals supplying the radial artery. This can be seen in Fig. 2, although it was not visualized intraoperatively. The patient underwent an emergent interposition vein graft repair between the brachial artery and the ulnar artery, along with median and ulnar nerve repair, muscle repair, and skin grafting. At 42 months follow-up, the patient continues to do well without signs of arterial insufficiency.

Case 3: Patient 3, acute evaluation of foot crush injury with foot ischemia and preoperative evaluation of recipient vessels prior to microsurgical flap transfer

A 3-year-old female sustained a crush injury to the left foot. Physical examination revealed the left foot to have signs of devascularization (Fig. 3). CTA found truncation of the dorsalis pedis and both the proximal dorsal and volar branches of the plantar artery, without reconstitution of the plantar arch. The dorsalis pedis artery was reconstituted distally, whereas the plantar arch was not. Interposition vein

Table 1 Individual patient data.

Patient	Age (years)	Diagnosis	CTA Timing	CTA Site	CTA Results	Operation	CTA/op Findings Agree?	Complications	Follow-up Time (months)
1	17	Degloving injury (forearm)	Subacute	RUE	Normal	Free rectus muscle flap + stsg	Yes	None	49
2	16	Laceration (forearm)	Acute	RUE	Transected brachial, radial, & ulnar aa w/ distal reconstitution of radial & ulnar aa	Brachial aa repair with vein graft	Yes	None	42
3	3	Crush injury (foot)	Acute	LLE	Proximally truncated dorsalis pedis aa; truncated posterior tibial aa after bifurcation into distal & volar branches; no reconstitution of palmar arch	Dorsalis pedis aa reconstruction with vein graft; followed by free rectus muscle flap + stsg at later date	Yes	None	41
4	5	Supracondylar fracture	Acute	RUE	Distally truncated brachial aa at radial head with distal reconstitution of radial & ulnar aa with normal arch	Brachial aa exploration + repair of brachioradialis	Yes	None	40
5	10	Crush injury (leg & foot)	Subacute	LLE	Normal	Free latissimus muscle flap + stsg	Yes	None	37
6	10	Dog bite (knee)	Subacute	RLE	Normal	Pedicle medial + lateral gastrocnemius muscle flaps + peroneal nerve exploration	Yes	None	24
7	4	Degloving injury (foot)	Subacute	LLE	Completely disrupted dorsalis pedis aa; normal posterior tibial aa & branches	Free rectus muscle flap + stsg	Yes	None	14
8	7	Supracondylar fracture + Volkmann's contracture	Elective	LUE	Occluded brachial aa in middle & distal portions	Brachial aa exploration + flexor tendon lengthening	Yes	None	7
9	13	Degloving injury (ankle)	Subacute	RLE	Normal	Free latissimus muscle flap + stsg	Yes	None	7
10	3	Supracondylar fracture	Elective	RUE	Occluded brachial aa at distal arm, with ulnar aa reconstituted by profunda brachial aa branches and radial aa reconstituted by geniculate collaterals	Brachial aa reconstruction w/ vein graft + median/ulnar neurolysis + flexor tendon release	Yes	None	5

In all patients, CTA findings agreed with intraoperative findings, and operative planning guided by CTA findings led to good clinical results with no missed vascular injuries or other complications. For CTA timing, *acute* refers to imaging within 1 day of injury; *subacute*, from 1 to 7 days after injury; and *elective*, more than 7 days after injury

CTA = computed tomography angiography, RUE = right upper extremity, LUE = left upper extremity, RLE = right lower extremity, LLE = left lower extremity, aa = artery, stsg = split-thickness skin graft

Figure 1 Patient 1, a 17-year-old female with a degloving injury to the right forearm. CTA revealed intact vasculature. The patient underwent coverage with a free rectus muscle flap and skin graft. **a**

preoperative picture showing extent of injury. **b** preoperative CT angiogram. **c** intraoperative picture after flap inset.

graft between the proximal and distal stumps of the dorsalis pedis artery restored distal foot perfusion, sparing amputation. A second CTA was performed prior to free rectus flap transfer. At 40 months follow-up, the foot and all toes remain viable.

Discussion

Extremity trauma in children is common. Epidemiologic studies of motor vehicle accidents report that 18% of all associated pediatric injuries involve the extremities [22]. Some of these clinical situations have significant risk of vascular compromise. In the upper extremity, supracondylar humeral fractures of high severity (grade II or III) are associated with brachial artery injury in 3–4% [7, 12] and can lead to Volkmann's contracture. In the lower extremity, tibial fractures seen in trauma patients have up to 12% coincidence of tibial artery injury [16], whereas knee dislocations are often associated with popliteal artery injury [15]. Penetrating injuries such as knife and gunshot wounds can also lead to ischemia. In all cases, visualization of the

vascular anatomy of the extremity is required prior to flap reconstruction in acute and chronic wounds.

The current study documents the utility of CTA for evaluation of extremity trauma in the pediatric population. Our indications for CTA in this population were any patient with suspected vascular injury to an extremity, based on mechanism and clinical exam, without known allergy to contrast dye. We did not use a minimum age in selecting these patients. In all 10 patients, irrespective of age, referral source, and type of injury, CTA successfully screened for and detected vascular injuries of the upper and lower extremities, affording appropriate reconstructive surgical treatment planning. Using intraoperative findings as the standard, CTA had 100% sensitivity. Using clinical follow-up and the intraoperative findings as references, CTA had 100% specificity. The information provided by CTA assisted in surgical planning, providing rapid localization of the site of vascular injury and assisting in choice of recipient vessels for repair or free flap reconstruction.

By obviating the need for catheter-based angiography in our study population, CTA provided several benefits. First, the pertinent vascular information was obtained noninvasively, eliminating the potential risk of iatrogenic vascular

Figure 2 Patient 2, a 16-year-old male with a deep laceration to the right proximal forearm. CTA revealed absent flow in the proximal brachial, radial, and ulnar arteries with distal reconstitution of the radial and ulnar

arteries. The patient underwent repair of the brachial artery with a vein graft. **a** CT angiogram reconstruction of soft-tissue injury utilizing soft-tissue windows. **b, c** preoperative CT angiograms.

Figure 3 Patient 3, a 3-year-old female with a crush injury to the left foot. CTA revealed truncation of both the dorsalis pedis artery and plantar artery branches arteries, without reconstitution of the palmar arch. The patient underwent reconstruction of the dorsalis pedis artery

with a vein graft, followed by a free rectus muscle flap with skin graft at a second operation. **a** intraoperative picture showing initial extent of injury. **b, c** preoperative CT angiograms. **d** postoperative picture after completion of operations.

injury. Second, CTA was obtained in a timely manner for patients from the emergency department, inpatient wards, and outpatient clinics. Third, CTA provided considerable cost-savings. At our institution, including professional fees, the average cost for catheter angiography is \$3,900, whereas that for CTA is \$1,200. CTA has a potentially greater impact on cost savings when considering that CTA provides a single diagnostic test to comprehensively evaluate vascular and nonvascular anatomy. Fourth, CTA yielded three-dimensional data sets that could be displayed and manipulated in any projection for accurate treatment planning and intraoperative reference. Fifth, CTA could be performed with minimal sedation in this population, with the youngest patients requiring only small doses of versed or pentobarbital, whereas the older pediatric patients required no sedation at all.

Catheter angiography is still used for evaluating blood flow distal to the proximal phalanges, where current CTA is not sensitive enough to delineate vascular changes. In our experience thus far, CTA has been able to visualize vessels as small as 0.5 mm. In the near future, as CTA technology advances with greater multirow detectors, it may replace standard angiography completely.

One potential limitation of using CTA in our study patients is that CTA is performed by static acquisition. Acquiring dynamic information is not possible with CTA at its current state. This precludes (1) direct evaluation of

collateral flow and (2) vasodilatory maneuvers to confirm vasospasm. Nonetheless, collateral flow and vasospasm can be reliably identified with CTA. When vessels are occluded, the major routes of collateral flow are recognized by identifying potential pathways that have increased caliber size. Vasospasm is diagnosed by seeing gradual effacement and then restoration of the luminal size without abrupt occlusion. Using these criteria, we were able to identify significant routes of collateralization and accurately diagnose vasospasm.

If vasospasm is suspected clinically but cannot reliably be diagnosed on CTA, catheter angiography may be indicated. Alternatively, magnetic resonance angiography (MRA) and duplex ultrasound (US) can be obtained to provide physiologic data. MRA and US are other noninvasive modalities that can be used to evaluate the vasculature in place of catheter angiography. In distinction to CTA, both afford dynamic and static vascular assessment. However, in the setting of trauma, these modalities are not routine substitutes for CTA. Although MRA lacks ionizing radiation and avoids nephrotoxic contrast material, magnetic resonance imaging is not as readily available, is not typically in close proximity to the emergency department, requires longer scan times, and is not conducive for cardiopulmonary resuscitation. US also avoids radiation and iodinated contrast exposures; in addition, it is portable. However, duplex US is operator-dependent, cannot gener-

ate three-dimensional vascular maps, and has limited coverage in each image display. Other limitations of CTA include the potential complications of contrast allergy and nephrotoxicity, though none were seen in this series.

There are several limitations with our study. First, our study population was small, comprised of 10 patients. Second, the study design did not include direct comparisons with conventional catheter angiography, MRA, or US. Such comparisons would be useful to further validate CTA performance. Third, in most patients with normal CTA findings, vessels were not operatively explored, so there was no direct intraoperative corroboration of CTA interpretations. Instead, we assessed the accuracy of CTA for normal interpretations by visualizing viable tissues intraoperatively and using long-term clinical follow-up to determine if any vascular injuries were missed by CTA (false negatives).

Despite these limitations, our results demonstrate that CTA is a useful preoperative modality to evaluate pediatric patients with suspected traumatic extremity vascular injury. As determined by intraoperative findings and clinical follow-up, excellent accuracy can be attained. CTA can provide high clinical confidence to plan reconstructive surgical procedures at reasonable cost. For these reasons, CTA may be a preferred alternative modality to conventional catheter angiography for extremity trauma in children.

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