Prospective Evaluation of Multidetector Computed Tomography for Extremity Vascular Trauma

Kenji Inaba, MD, Bernardino C. Branco, MD, Sravanthi Reddy, MD, John J. Park, MD, PhD, Donald Green, MD, David Plurad, MD, Peep Talving, MD, PhD, Lydia Lam, MD, and Demetrios Demetriades, MD, PhD

Background: Multidetector computed tomographic angiography (MDCTA) is increasingly being used for the assessment of extremity vascular injury. However, to date, there are only retrospective series and a single small prospective study evaluating its efficacy. Therefore, the objective of this study was to prospectively evaluate the ability of MDCTA to detect arterial injury in the injured upper and lower extremities.

Methods: After institutional review board approval, all trauma patients aged 16 years or older admitted to a Level I trauma center who sustained extremity trauma and underwent initial evaluation with a 64-channel MDCTA from March 2009 to June 2010 were prospectively enrolled. The sensitivity and specificity of MDCTA were tested against an aggregate gold standard of operative intervention, conventional angiography, and clinical follow-up.

Results: During the 20-month study period, 635 patients with extremity trauma underwent a structured clinical examination. Hard signs of vascular injury were observed in 5.5% of patients with a 97.1% incidence of clinically significant injury requiring operative intervention. Eighty-three percent of patients had no signs of vascular injury with no missed injuries detected during follow-up. Eighty-nine MDCTAs were performed in the remaining 73 patients (11.5%) with soft signs. The mechanism of injury was penetrating in 69.9% (42 gunshot wound, 5 stab wound, and 4 shotgun). There were 24 positive studies, 23 of which were confirmed at operation (5 brachial artery injuries, 2 radial, 1 ulnar, 1 external iliac, 2 common femoral, 5 proximal superficial femoral, 2 distal superficial femoral, 4 popliteal, and 1 posterior tibial artery injury). A left posterior tibial artery occlusion was managed nonoperatively. There were 58 negative studies with clinical follow-up available in 100%, for a mean of 10.6 days ± 11.7 days (median, 6 days; range, 1–41 days). MDCTA was nondiagnostic in seven patients (9.6%), five secondary to artifact from retained missile fragments (3 shotgun and 2 gunshot wound), and two secondary to technical errors in reformatting. In the absence of artifact, MDCTA achieved 100% sensitivity and 100% specificity in detecting all clinically significant arterial injuries.

Conclusions: Physical examination is critical in the decision-making process for the injured extremity and can accurately reduce unnecessary imaging. If imaging is required, MDCTA is a sensitive and a specific noninvasive modality for arterial evaluation and may replace conventional angiography as the diagnostic modality of choice for the evaluation of the acutely injured extremity.

Key Words: Extremity trauma, Vascular injuries, Diagnostic imaging, Computed tomography angiography, Multidetector CT.

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retrospective case series with only a single prospective study of 21 patients evaluating the diagnostic capability of contemporary multidetector CT technology.4–12

Therefore, the objective of this study was to prospectively evaluate the ability of MDCTA to detect arterial injury in the injured upper and lower extremities. Our hypothesis was that MDCTA is both a sensitive and a specific noninvasive imaging modality for the evaluation of the acutely injured extremity.

PATIENTS AND METHODS

After institutional review board approval, all patients who sustained extremity trauma presenting to the Los Angeles County and to the University of Southern California Medical Center, a Level I trauma center, between January 1, 2009, and August 31, 2010 (20 months), were prospectively screened for inclusion in this study. The inclusion criteria for enrollment were (1) age 16 years or older, (2) penetrating injury mechanism (gunshot wound [GSW], shotgun, or stab wound) or crush injury to extremities or any other blunt mechanism resulting in a long bone fracture or dislocation, (3) injury site between mid-clavicle and wrist for the upper extremity or between the inguinal ligament and ankle for the lower extremity. Patients requiring emergent cavitary surgery were excluded from the study.

During the study period, all patients meeting inclusion criteria were evaluated by an in-house attending trauma surgeon and managed according to the study protocol. Patients underwent a structured clinical examination and were categorized as having “hard signs,” “soft signs,” or “no signs” of vascular injury. Hard signs of vascular injury included absent distal pulses, limb ischemia, active hemorrhage, expanding or pulsatile hematoma, bruise or thrill in the area of injury, compartment syndrome, or shock unresponsive to initial fluid resuscitation and attributable to the extremity injury. These patients underwent immediate surgical exploration without imaging.

Patients with no signs of vascular injury included those who were completely asymptomatic with an ankle–brachial index (ABI) or brachial–brachial index (BBI) ≥0.9. These patients underwent observation without imaging for a minimum of 24 hours before hospital discharge.

All other patients were considered to have soft signs of vascular injury. These signs included venous oozing, nonexpanding or nonpulsatile hematoma, diminished distal pulses, or an abnormal ABI or BBI. These patients all underwent initial evaluation with MDCTA (Toshiba Aquilion 64 CFX multislice CT scanner, Toshiba Medical, Japan). The extremity MDCTA protocol was standardized throughout the study period. The following parameters were used: 120 kVp, 200 mAs to 400 mAs (depending on the size of patient, using dose modulation), gantry revolution speed of 0.5 second, beam pitch 0.828, beam collimation of 64 mm × 0.5 mm, variable field of view (depending on size of patient), and standard body kernel. Through a line suitable for power contrast injection (18 or 20 gauge peripheral intravenous line in the antebrachial fossa or a central venous catheter that has been approved by the manufacturer for power injection) 75 mL to 100 mL of Iohexol iodinated intravenous contrast material (Omnipaque 350; GE Healthcare, Princeton, NJ) was injected at a rate of 4 mL/s followed by a 40 mL saline flush by a Medrad power injector (Spectris; Medrad, Indianola, PA). We use contrast bolus tracking with a trigger threshold of 180 HU, with the region of interest placed in the abdominal aorta at the L2–L3 level. Reconstruction with section thickness of 1 mm and 2 mm in the axial, coronal, and sagittal planes was performed, and additional postprocessing was performed by the radiologist on a Vitrea reformatting workstation (Vital Images, Plymouth, MN) to create volume renderings, maximum-intensity projections, and curved planar reformations as needed. Reconstruction was performed by an attending radiologist or interventional radiology fellow and the final attending read was used for the analysis. Admission data collected included age, gender, injury mechanism, systolic blood pressure and Glasgow Coma Scale (GCS) score, hemoglobin, international normalized ratio, base deficit, and lactate. Findings from the structured physical examination performed at admission were documented for each patient. All patients included in the study were followed up throughout their hospital stay. All operative procedures and the results of imaging were documented. Injury Severity Score (ISS), extremity Abbreviated Injury Scale (AIS), hospital length of stay, intensive care unit length of stay, and mortality were recorded.

Continuous variables were dichotomized using the following clinically relevant cut-points: age (55 years or older vs. younger than 55 years), systolic blood pressure at admission (<90 mm Hg vs. ≥90 mm Hg), GCS score at admission (≤8 vs. >8), ABI or BBI (≥0.9 or <0.9), ISS (≥16 vs. <16), and extremity AIS (≥3 vs. <3).

The MDCTA sensitivity and specificity were tested against an aggregate gold standard of the final diagnosis at discharge, which included operative exploration, catheter-based angiography results, and clinical follow-up. Descriptive statistics were applied. Values are reported as means ± SD for continuous variables and as percentage for categorical variables. All analyses were performed using the Statistical Package for Social Sciences (SPSS Mac), version 18.0 (SPSS Inc., Chicago, IL).

RESULTS

During the 20-month study period, a total of 635 (6.8% of total trauma admissions) patients admitted to the Los Angeles County and to the University of Southern California Medical Center were prospectively identified as having sustained extremity trauma meeting criteria for inclusion in this study. Of these, 26.1% (166) were upper extremity and 73.9% (469) lower extremity injuries. Thirty-five patients (5.5%) had hard signs of vascular injury and underwent immediate surgical exploration (Fig. 1). All but one was found to have a vascular injury intraoperatively. These injuries included one axillary, five brachial, two radial, two ulnar, four common femoral, one profunda femoral, three proximal superficial femoral, five distal superficial femoral, seven popliteal, two tibiofemoral and one posterior tibial artery as well as two brachial, one cephalic, one basilic, four femoral, and
two popliteal veins. A total of nine patients had combined arterial and venous injuries. One patient in shock despite fluid resuscitation had an isolated large open wound in the right upper arm with an underlying comminuted humerus fracture. However, no significant vascular injuries were found at operation.

Five hundred twenty-seven patients (83.0%) had no signs of vascular injury; all were observed and discharged without the development of a vascular complication. Clinical follow-up was available for a mean of 3.1 days (median, 2 days; range, 1–101 days) with no delayed presentation of injury seen.

A total of 73 patients (11.5%) underwent evaluation with MDCTA (Fig. 1). Of these, 62 (84.9%) had soft signs of vascular injury and 11 (15.1%) were protocol violations. The protocol violations were patients who were asymptomatic with normal ABI or BBIs but nevertheless underwent MDCTA at the attending surgeon’s discretion for a trajectory in proximity to a vascular structure. All the MDCTAs performed for proximity only were negative for injury.

The average age of the patients undergoing MDCTA was 30.3 years (median, 12.7 years) and 87.7% were men. The average GCS score was 15 (median, 1–15) and 35.6% had an ABI or BBI <0.9. The mean ISS for this population was 10.0 (median, 8.1–13) and 38.4% had an extremity AIS score ≥3 (Table 1). A total of 38.4% had extremity fractures and 13.6% had dislocations. The mechanism of injury was penetrating in 69.9% (n = 51), predominantly from a GSW (57.5% [n = 42]). Of the blunt mechanisms, the most common were a motorcycle crash (n = 6), motor vehicle collision (n = 5), fall (n = 5), and auto versus pedestrian (n = 5).

The most common soft sign in this population was a nonexpanding or nonpulsatile hematoma and abnormal ABI or BBI (35.6% each) followed by venous oozing (21.9%) and diminished pulses (19.2%; Fig. 2). Of those undergoing MDCTA, 46 patients had 62 lower extremity evaluations and 27 patients had 27 upper extremity eval-

Figure 1. Study outline. OR, operating room.

### TABLE 1. Demographic, Clinical Data, and Outcome for Patients (n = 73) Undergoing Evaluation With MDCTA

| Age (y), mean ± SD; median (range) | 30.3 ± 12.7; 27 (16–77) |
| Age ≥55 years (%) | 1.4 |
| Male (%) | 87.7 |
| Penetrating (%) | 69.9 |
| SBP on admission, mean ± SD; median (range) | 124.5 ± 22.7; 124.9 (76–174) |
| SBP on admission <90 mm Hg (%) | 8.2 |
| GCS on admission, mean ± SD; median (range) | 15 ± 1; 15 (11–15) |
| ABI or BBI on admission <0.9 (%) | 35.6 |
| Hgb on admission (mg/dL), mean ± SD; median (range) | 13.2 ± 2.0; 13.5 (7.2–16.5) |
| INR on admission, mean ± SD; median (range) | 1.1 ± 0.2; 1.1 (1.0–1.2) |
| Base deficit on admission (mEq/L), mean ± SD; median (range) | 4.8 ± 3.2; 4.1 (–2; 13) |
| Lactate on admission (mmol/L), mean ± SD; median (range) | 3.0 ± 2.1; 2.6 (1–11) |
| ISS, mean ± SD; median (range) | 10.0 ± 8.1; 10.0 (1–35) |
| Extremity AIS ≥3 (%) | 13.6 |
| HLOS, mean ± SD; median (range) | 10.4 ± 11.6; 6 (1–54) |
| ICU LOS, mean ± SD; median (range) | 5.0 ± 3.3; 4 (1–26) |
| Mortality (%) | 1.4 |

SBP, systolic blood pressure; Hgb, hemoglobin; INR, international normalized ratio; HLOS, hospital length of stay; ICU, intensive care unit.

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The most common injury site evaluated with MDCTA was the thigh (46.6%) followed by the upper arm and knee (17.8% each; Fig. 3).

Overall, the sensitivity and specificity of MDCTA in detecting clinically significant arterial injury were both 100.0%. There were 24 positive studies in 22 patients, with all but one confirmed at operation. One patient had a complete occlusion of the left posterior tibial artery diagnosed on MDCTA and was observed (Fig. 4). The findings confirmed at operation included five brachial artery injuries, two radial, one ulnar, one external iliac, two common femoral, five proximal superficial femoral, two distal superficial femoral, four popliteal, and one posterior tibial artery injuries. The injuries detected included 4 lacerations with contrast extravasation, 14 occlusions, 4 pseudoaneurysms, 1 arteriovenous fistula, and 1 intimal injury. A total of 68.1% patients had an associated extremity fracture and 9.1% had a dislocation.

There were 58 negative studies performed in 44 patients. Clinical follow-up was available in these patients for a mean of 10.6 days ± 11.7 days (median, 6 days; range, 1–41 days). At the attending surgeon’s discretion, one of these was further evaluated with conventional catheter-based angiography, which was negative. A total of 18 patients with negative studies returned to the outpatient clinic for follow-up (41%; Fig. 4).

MDCTA was nondiagnostic in seven patients (9.6%). Five were due to artifact from retained missiles (3 shotgun and 2 GSW) and two were due to errors in reformatting.
patient in this group was further evaluated with conventional angiography, which was positive for a brachial artery injury. In two cases, although the MDCTA did not definitively diagnose an injury caused by artifact, the patients underwent exploration due to highly suspicious tracts. One of these patients had a clinically significant injury. Four patients were subsequently observed without vascular complications. Again, although not definitive, these four MDCTAs were of low suspicion for injury, and on serial clinical examination, these patients remained asymptomatic.

If the inconclusive results due to artifact were treated as false negatives for the sensitivity calculation and, false positives for the specificity calculation, the pooled sensitivity and specificity of MDCTA for detecting vascular injury would be 82% and 92%, respectively.

**DISCUSSION**

Clinical examination is the mainstay of the diagnostic work-up for an injured extremity. Accurate decision-making requires an assessment of the vascular integrity, soft tissues, skeletal structure, and neurologic function of the limb. As demonstrated in a comprehensive series of studies on extremity vascular trauma by Frykberg’s group, with a mean follow-up exceeding 9 years, clinical examination is critical for deciding when imaging is warranted. His work showed that there is no role for routine imaging of the injured extremity. In the majority of their patients, injuries occult to the physical examination were clinically insignificant. For those injuries that were clinically significant, and had a delay in diagnosis, there were no adverse outcomes associated with the delay in repair.

Patients enrolled in this study protocol underwent a structured clinical examination by their attending surgeon. They were then categorized as those with hard signs, soft signs, or no signs of vascular injury. The validity of this approach tested in this prospective series of 635 patients was one of the primary findings of this study. Those with hard signs proceeded directly to the operating room, those with soft signs underwent imaging with MDCTA and those with no signs underwent a minimum of 24 hours of observation. Whereas only 5.5% arrived with hard signs of vascular injury, this finding had a high yield for clinically significant injuries with 97.1% having an injury requiring repair, bypass, or ligation. The largest group of patients were those who arrived with no signs of vascular injury, comprising 83% of the study population. For these patients, with an average 3.1 days of close observation, no clinically significant missed injuries were detected. For the remaining 11.5% who underwent MDCTA, the majority had soft signs of vascular injury. In this group, however, 15.1% of these patients were protocol violations. These patients were asymptomatic with normal ABI and BBIs who should have been observed without imaging. In each case, the attending trauma surgeon ordered MDCTA evaluation for proximity, all of which were negative. This finding validates previously published work emphasizing the poor discriminating ability of proximity for detecting clinically significant vascular injury.

In summary, for this series of patients undergoing a structured physical examination, the physical findings were highly accurate in determining which patients warranted imaging with MDCTA. Those with hard signs require operative intervention without preoperative imaging. The only exception to this may be patients who have sustained a multilevel injury, shotgun injury, or a crush without a fracture; in these patients, MDCTA or on-table angiography will help in planning the surgical approach. For patients with a negative examination, a clinically significant injury is highly unlikely and imaging is likewise not required.
For patients who present with soft signs of vascular injury, MDCTA was highly sensitive and specific for clinically significant injuries. In reviewing the data available on the sensitivity of CT-based angiography, although universally positive, the vast majority of the studies are retrospective in design. For prospective studies, only two series of patients using outdated technology and a single prospective study of 21 patients using contemporary MDCTA have been published. The earliest work used single-detector CT scanners, including two prospective series by Soto et al. and a retrospective study by Busquets et al. These studies demonstrated sensitivities ranging from 90% to 100% using a gold standard of operative exposure and conventional angiography. The remainder of the studies used much improved MDCTA technology. In a retrospective study from the Ryder Trauma Center, 63 MDCTAs were performed for lower extremity injuries of which 45.8% were penetrating. The MDCTA was diagnostic in 98.4% of cases. With follow-up available in 89.5% of patients for a mean of 48.2 days (range, 5 days–287 days), MDCTA achieved a 100% sensitivity and 100% specificity for injuries, including lesions below the trifurcation. A subsequent retrospective study of 87 predominately blunt patients from Austria demonstrated a sensitivity of 99% and specificity of 87%. Similar results with 100% sensitivity for a retrospective series of 34 patients with extremity trauma was reported from the group at Stanford. In a retrospective evaluation of MDCTA for 59 patients with only upper extremity trauma, although a formal sensitivity calculation was not reported, no missed injuries were detected during follow-up. In the pediatric population, a retrospective evaluation was performed in 78 trauma patients younger than 18 years, of which 52.6% were penetrating. These patients underwent either neck or extremity evaluation with MDCTA, with a sensitivity of 100% and a specificity of 93%. Finally, in the only prospective evaluation of multidetector technology for the acute evaluation of the injured extremity, 21 patients, of which 91% were penetrating, had 22 limbs (32% upper) evaluated. Ninety-six percent of the examinations were diagnostic and all were confirmed by conventional angiography or operative exploration. The sensitivity and specificity was 100% with both a cost and time savings in favor of MDCTA. Therefore, the aggregate sensitivity in the available literature for multiple detector studies ranges from 99% to 100% with a specificity of 87% to 100%. In this, the largest prospective study to date examining MDCTA, the sensitivity using a composite gold standard of all imaging, operative exposure, and clinical follow-up was 100% with a specificity of 100%. This included both upper and lower extremities, as well as the small caliber arteries distal to the elbow and the knee.

To the best of our knowledge, there has been no direct comparison of the radiation burden associated with MDCTA when compared with traditional catheter based angiography for extremity evaluation. The direct impact of the radiation exposure is therefore unknown. Although there are differences in protocol, when compared with catheter-based angiography for nontraumatic extremity evaluation, for peripheral arterial occlusive disease, and for bilateral extremity run-offs, a decrease in radiation exposure has been demonstrated. In a study using a 16-detector row CT, the radiation dose for CT angiography (1.6–3.9 mSv) was approximately a quarter of that associated with conventional angiography (6.4–10.0 mSv).

With MDCTA, artifact remains a practical shortfall. In almost 10% of cases, technical issues precluded a definitive diagnosis. The majority of these were due to retained fragments, in particular shotgun injuries, a problem highlighted in previous studies. However, although not definitive, in most cases, the images were sufficient to assist in decision-making. In these cases, follow-up with directed conventional angiography may be considered. In two cases, technical problems occurred with formatting. This study was initiated soon after moving to a new facility with new CT scanners and protocols. These technical errors occurred early in patient accrual and were due to a lack of familiarity with the protociling, an error that should be expected for any center attempting to implement this technology. If these cases where artifact precluded a definitive diagnosis was included in the sensitivity calculation, the overall aggregate sensitivity and specificity would be 82% and 92%, respectively.

This study was limited by the reliance on an aggregate gold standard rather than conventional angiography and surgery. For positive MDCTA findings, operative exposure confirmed all but one injury. The only injury not confirmed at operation was a posterior tibial artery occlusion that was not clinically significant. For the negative MDCTA cases, confirmation with a conventional angiogram would have been ideal. However, with the bulk of the available evidence attesting to a sensitivity of upward of 100%, it is difficult to justify the cost, time, risk, and radiation burden of performing a conventional angiogram for all patients and therefore clinical follow-up was used. As with most trauma studies, follow-up after discharge was problematic. Although all patients were counseled about the importance of follow-up and the need to return should there be any changes in symptoms, the actual return rate to clinic was poor. Therefore, although all patients had a minimum of 24 hours of close observation, it is conceivable that an injury was missed by the MDCTA and repaired in a delayed fashion at an outside facility, which would decrease the calculated sensitivity of 100%. Finally, as all medical imaging technology evolves, there is no doubt that there will be improvements in the speed and accuracy with which even the smallest injury will be detected and characterized, allowing both enhanced preoperative planning and safer nonoperative management. There is however the real risk that clinically insignificant anatomic abnormalities will be detected and that the radiation burden sustained by these patients will increase. It is therefore incumbent on us to ensure that careful reassessment of new technology occur with parallel clinical studies targeted not simply at improving the resolution of injuries but evaluating the clinical significance of the lesions being discovered.

In summary, physical examination is critical in the initial evaluation of the injured extremity. Hard signs of vascular injury effectively predict the need for operative intervention. Those with no signs can be safely observed. For
patients with soft signs, MDCTA is an effective imaging
modality. Within the limitations of the study design, all
clinically significant injuries were detected, no clinically
significant injuries were missed, and no patient underwent a
negative exploration based on a false-positive MDCTA.
These findings support, with a large prospectively collected
dataset, the high sensitivity and specificity of this imaging
modality for detecting arterial injuries in both the upper
and lower extremity. At our institution, MDCTA has replaced
traditional catheter-based angiography for evaluation of the
injured extremity.

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Dr. George Velmahos (Boston, Massachusetts): Velmahos, Boston. Kenji, let me join everybody else on congratulating you for a beautiful presentation. Your Hollywood flair really works.

Did I understand well that even with a negative angiogram, you still followed the patient up for 24 hours? If indeed this is your practice, why do you not feel comfortable to discharge a patient from the ER after a negative angiogram?

Dr. Kenji Inaba (Los Angeles, California): Thank you so much for those comments. If I could start off with Dave – and thanks for letting me think about the questions before I got up here – I agree completely regarding the sensitivity and specificity calculation.

You’re absolutely right. We sat down to discuss this at length when we were designing the study because we knew that artifact was going to pop up as a significant issue from all of the previous studies that have been done.

So, we decided that we would take the most practical approach possible because we knew that these artifacts would be there, and that when they are there, you know they are there and can evaluate these patients using an alternative modality like catheter based angio. Most importantly, we knew that because you can easily see the artifact, this would not mislead our clinical management of these patients.

So because of that we designed our analysis so that when we saw an artifact or a mis-reconstruction, they would be deemed as such, and excluded from our sensitivity calculation.

As far as the multiple comparisons I fully agree with that as well.

You know, with all the work that Dr. Frykberg has done on the physical examination plus the eight other CT studies that are out there we just could not justify getting a CT angio on the entire dataset of the 635 patients that we enrolled, as much as we would have liked to.

That would have been the ideal way to do it but we just couldn’t justify it. But I think that’s a very important point.

Dr. Blake, only 1 patient that went to the OR with hard signs but did not have an arterial or a venous injury. This patient was in shock and had an isolated right upper extremity injury with a humeral fracture but no vascular injury.

And the confirmatory duplex as opposed to more invasive angio, irrespective of sensitivity issues, logistically, even if we wanted to, we couldn’t – we work at LA County and just getting a duplex is a difficult sort of thing. To be able to duplex everybody for the purposes of this study is a great idea but just couldn’t be done.

Dr. Saxe, the immediate recons, absolutely. They get done for us immediately at the work station while we’re there. So practically for the clinical team we run the CT angio and by the time the patient is moved back onto their gurney all the recons are up.

It’s all protocolized now and although the first month or two was a little bit difficult getting used to the scanners but once the protocol was in place it’s actually super smooth now.

Samir, thanks, and as far as the stents, we very rarely stent at our institution due to multiple reasons, especially for peripheral vascular injuries. The vast majority of these patients, as you saw from our case series, go directly to the operating room once a diagnosis is made.

But I think you highlight a very important point. The CT angio is purely a diagnostic test and once that’s done if something therapeutic is going to be done through interventional radiology means, then a second run of contrast and a second run of radiation will be required.

And, finally, George, yes, all negative studies were followed up for a mean of 10 days or so, ranging from a minimum of one day to 41 days. Would having just the CTA being negative be sufficient for us to send our patients home? I think based on our aggregate experience now over the last 20 months plus the eight other studies with sensitivities ranging from 99 to 100 percent I think we feel very comfortable that the negative predictive value of this test is very good.

And based on that we’ve actually fully gone to using just CT angios to screen. And if a patient has a negative CT angio, despite having soft signs, they will be sent home after a 24-hour observation period.