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ORIGINAL CONTRIBUTION

Diagnostic Yields, Charges, and Radiation Dose of Chest Imaging in Blunt Trauma Evaluations

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Abstract

Background: Chest radiography (CXR) is the most common imaging in adult blunt trauma patient evaluation. Knowledge of the yields, attendant costs, and radiation doses delivered may guide effective chest imaging utilization.

Objectives: The objectives were to determine the diagnostic yields of blunt trauma chest imaging (CXR and chest computed tomography [CT]), to estimate charges and radiation exposure per injury identified, and to delineate assessment points in blunt trauma evaluation at which decision instruments for selective chest imaging would have the greatest effect.

Methods: From December 2009 to January 2012, we enrolled patients older than 14 years who received CXR during blunt trauma evaluations at nine U.S. Level I trauma centers in this prospective, observational study. Thoracic injury seen on chest imaging and clinical significance of the injury were defined by a trauma expert panel. Yields of imaging were calculated, as well as mean charges and effective radiation dose (ERD) per injury.

Results: Of 9,905 enrolled patients, 55.4% had CXR alone, 42.0% had both CXR and CT, and 2.6% had CT alone. The yields for detecting thoracic injury were CXR 8.4% (95% confidence intervals [CIs]) = 7.8% to 8.9%), chest CT 28.8% (95% CI = 27.5% to 30.2%), and chest CT after normal CXR 15.0% (95% CI = 13.9% to 16.2%). The mean charges and ERD (millisievert [mSv]) per injury diagnosis of CXR, chest CT, and chest CT after normal CXR were $3,845 (0.24 mSv), $10,597 (30.9 mSv), and $20,347 (59.3 mSv), respectively. The mean charges and ERD per clinically major thoracic injury diagnosis on chest CT after normal CXR were $203,467 and 593 mSv.

Conclusions: Despite greater diagnostic yield, chest CT entails substantially higher charges and radiation dose per injury diagnosed, especially when performed after a normal CXR. Selective chest imaging decision instruments should identify patients who require no chest imaging and patients who may benefit from chest CT after a normal CXR.

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Almost universally recommended by Advanced Trauma Life Support guidelines, chest imaging (chest radiography [CXR], and chest computed tomography [CT]) is the most common imaging in adult blunt trauma patient evaluation.[1] Despite its frequent use, CXR has received little evidence-based utilization review in comparison to head and spine imaging. Overutilization of chest imaging may unnecessarily expose patients to ionizing radiation, incur greater trauma evaluation costs, and prolong emergency department (ED) lengths of stay.[2–8] The anatomic field of trauma chest CT includes organs that are particularly radiation-sensitive, and investigators have quantified the potential cancer risk associated with the performance of nontrauma chest CT.[2,9]

Decision instruments have been shown to safely direct selective diagnostic trauma imaging.[10,11] The ultimate goal of this study was to develop safe and efficient protocols for chest imaging in adult blunt trauma evaluation. In this regard, we derived a decision instrument that predicted intrathoracic injury in adult blunt trauma patients with high sensitivity.[12] As part of our subsequent validation study of this decision instrument, we planned to assess current blunt trauma chest imaging practice in terms of yields, financial considerations, and risks (predominantly radiation exposure) and thereby identify other trauma evaluation points (beyond the initial decision of whether to image or not to image) that would be most amenable to decision instrument development. Specifically, we sought to: 1) determine the diagnostic yields of individual components of chest imaging (CXR, chest CT, and chest CT after normal CXR) in adult blunt trauma patient evaluation, 2) estimate radiation exposure and hospital charges per injury identified with these three components, and 3) delineate trauma chest imaging assessment points for which selective chest imaging decision instruments would have the greatest effect (considering calculated yields, estimated charges, and radiation dose per injury diagnosed of the three chest imaging components).

METHODS

Study Design
This study was a preplanned analysis of data derived during the validation of the NEXUS Chest decision instrument, a multicenter, prospective cohort study conducted at nine U.S. Level I trauma centers.[13] We deidentified and recorded data in a manner that precluded individual patient identification and received institutional review board approval with a waiver of informed consent at all sites (except for consent for phone follow-up of the sample of subjects described under work-up bias below). We retained responsibility for all aspects of the study design, implementation, and analysis, as well as manuscript preparation and submission, without influence from the funding source.

Study Setting and Population
From December 2009 to January 2012, we used a systematic block-sampling method (7 a.m. to 11 p.m.) to enroll patients with the following inclusion criteria: 1) age >14 years, 2) blunt trauma occurring within 24 hours of ED presentation, and 3) receiving chest imaging (CXR or chest CT) in the ED as part of blunt trauma evaluation.

Study Protocol
Outcome Determination. Trauma imaging, particularly CT, may diagnose minor injuries that may not be clinically meaningful, e.g., isolated spinous process fractures.[3,14] To address imaging yield in terms of clinical relevance, we convened an expert trauma panel consisting of 10 associate professor level or higher trauma surgeons and emergency physicians, who defined, a priori, thoracic injuries seen on chest imaging as pneumothorax, hemothorax, aortic or great vessel injury, two or more rib fractures, ruptured diaphragm, sternal fracture, and pulmonary contusion or laceration.[12,13]

We then generated a list of thoracic injuries seen on chest imaging paired with management changes and interventions (e.g., hemothorax with chest tube placement). Trauma expert panel members independently reviewed this list and assigned one of the following values to each injury/intervention pair: major clinical significance = 2 points, minor clinical significance = 1 point, and no clinical significance = 0 points. We calculated the means for these injury/intervention pairs (rounded to the second decimal place) and deemed mean scores of 1.50 to 2, 0.50 to 1.49, and 0 to 0.49 to represent injuries with major, minor, and no clinical significance, respectively (see Table 1 for this classification).

We used final radiologic interpretations by board certified radiologists (blind to subject enrollment) to determine the outcome of thoracic injuries seen on chest imaging. We classified subjects who had more than one CXR or CT in the ED as having thoracic injury if an injury was noted on any of the ED imaging studies. If subjects had discrepant CXR and chest CT results, we used the CT results as the true injury outcome standard. To minimize the detection bias that may have arisen from radiologists' readings of CXR after seeing injuries on CT, we only considered CXRs performed before CT in this analysis. In cases in which the CXR identified injuries (or suggested possible injury) that did not meet our explicit thoracic injury seen on chest imaging criteria, we classified subjects as being injury-negative by CXR, but having an abnormal CXR. In other words, when one rib fracture, a clavicle fracture, or a widened mediastinum was seen on a subject's CXR, we classified the subject as not having thoracic injury on CXR but still having an abnormal CXR (excluding him or her from the evaluation group of CT after normal CXR). In this analysis (in contrast to our validation study), injuries seen incidentally on upper abdominal CT but not noted on chest imaging, e.g., pneumothorax visualized on upper abdominal CT images, were not included.

With blinding to the types of imaging that subjects received, we determined the clinical outcome classification of subjects with thoracic injuries seen on chest imaging. We followed the principles of chart abstraction set forth by Gilbert et al.[15] and employed standard quality assurance methods, including multiple abstractor meetings and conferences, double data entry checking, random audits, and assessments of abstractor consis-

Table 1
Trauma Expert Panel Determination of Clinical Significance of Injuries Seen on Chest Imaging

Major clinical significance
   Aortic or great vessel injury (all are considered major)
   Ruptured diaphragm (all are considered major)
   Pneumothorax: received evacuation procedure (chest tube or other procedure)
   Hemothorax: received drainage procedure (chest tube or other procedure)
   Sternal fracture: received surgical intervention
   Multiple rib fracture: received surgical intervention or epidural nerve block
   Pulmonary contusion: received mechanical ventilation (including noninvasive ventilation) of any type for management
Minor clinical significance
   Pneumothorax: no evacuation procedure but observed as inpatient > 24 hours
   Hemothorax: no drainage procedure but observed as inpatient for > 24 hours
   Sternal fracture: no surgery but had in-hospital pain management or observed as inpatient > 24 hours
   Sternal fracture: no surgical intervention, no inpatient observation (pain managed on an outpatient basis)
   Multiple rib fracture: received in-hospital pain management or observation > 24 hours
   Multiple rib fracture: no surgical intervention, no inpatient observation, (pain managed on an outpatient basis)
   Pulmonary contusion or laceration: no mechanical ventilation but observed > 24 hours
No clinical significance
   Hemothorax: no surgical intervention, no inpatient observation (managed on an outpatient basis)
   Pneumothorax: no surgical intervention, no inpatient observation (managed on an outpatient basis)
   Pneumomediastinum without pneumothorax: no inpatient observation (managed on an outpatient basis)
   Pulmonary contusion or laceration: no mechanical ventilation, no surgical intervention, no inpatient observation (managed on an outpatient basis)

tency. When subjects had more than one thoracic injury, we classified them according to their highest category of clinically significant injury. When outcome assessments were ambiguous or conflicting (<0.01% of total assessments), we assigned the subject category by primary investigator consensus.

We defined yield of an imaging modality for thoracic injuries seen on chest imaging, thoracic injury with major clinical significance, and thoracic injury with major or minor clinical significance as the proportion of subjects diagnosed with injury by that modality divided by the total number of subjects who had that imaging modality. For example, the yield of CXR for injury equaled the number of subjects who had injury seen on CXR divided by the total number of subjects who had CXRs.

Work-up Bias. To evaluate work-up bias in terms of the potential missed injuries in trauma patients who did not receive chest imaging, and the possible missed injuries in subjects who had negative (no thoracic injuries seen on chest imaging) ED chest imaging results, we obtained written consent for phone follow-up of a sample of nonimaged blunt trauma patients and a sample of injury-negative subjects discharged from one of the study site EDs. We telephoned these subjects between 2 weeks and 3 months of ED discharge to determine whether or not they had seen health care providers, had received imaging tests, and had received any injury diagnoses since ED discharge. We also followed the hospital course of consecutive samples of admitted blunt trauma patients who had not received ED chest imaging and subjects who were admitted without injury seen on radiography, to determine whether they were subsequently diagnosed with thoracic injuries in the hospital (outside of the ED). Seeking to confirm an undetected injury rate of <2% with a 95% confidence interval (CI), we set, a priori, the sample size for both of these types of work-up bias at 200 subjects.

Charges and CT Radiation Dose. We obtained charges (institutional and professional fees) from each site for a single view trauma CXR and a trauma protocol chest CT and calculated the mean of these charges. We also obtained site estimates of effective radiation dose (ERD) for adult trauma protocol chest CT expressed in millisievert (mSv) per study and calculated the mean trauma chest CT ERD. Because ERD for CXR is not generally measured, we used a published estimate of 0.02 mSv for one-view trauma CXR ERD.[16] Because our objective was to accurately estimate charges and radiation exposure associated with future trauma imaging utilization, we used 2013 institution charges and chest CT doses from sites' latest model CT scanners. We calculated the mean charges and mean ERD per subject diagnosed with injury using the means above and the yields for each imaging modality.

Data Analysis

Our predetermined sample size of 9,718 subjects for the validation study was driven by the need to validate a highly sensitive decision instrument with a 0.5% CI around the sensitivity point estimate. We managed study data using Research Electronic Data Capture (RedCAP) tools hosted by the University of California at San Francisco.[17] We summarized and reported demographic data in aggregate form and performed descriptive data analyses using STATA version 9.0.

RESULTS

We enrolled 9,905 subjects, of whom 55.4% had CXR alone (48.6% with CXR alone and 6.7% with CXR and abdominal CT, but no chest CT), 42.0% had both CXR and chest CT, and 2.6% had chest CT without CXR. We found thoracic injuries in 1,478 (14.9%) subjects, including 363 (3.7%) deemed to be of major clinical significance, 1,079 (10.9%) of minor clinical significance, and 36 (0.4%) of no clinical significance (see Table 2 for sub-

Table 2
Subject Characteristics (N = 9,905)

Characteristic	n (%)
Male sex	6,220 (62.8)
Age (yr), median (IQR)	45 (29–60)
Mechanism of trauma	
Motorized vehicle accident	4,348 (43.9)
Fall	2,724 (27.5)
Pedestrian struck by motorized vehicle	1,060 (10.7)
Bicycle accident	624 (6.3)
Struck by blunt object, fists, or kicked	574 (5.8)
Admitted to hospital	5,173 (52.2)
Survived to hospital discharge	4,877 (94.3)
Thoracic injuries seen on chest imaging	
Two or more rib fractures	996 (10.1)
Pulmonary contusion or laceration	590 (6.0)
Pneumothorax	527 (5.3)
Sternal fracture	212 (2.1)
Hemothorax	207 (2.1)
Aortic or great vessel injury	15 (0.2)
Ruptured diaphragm	6 (0.1)

IQR = interquartile range.

ject characteristics). Under our assessment for work-up bias, we obtained follow-up on 221 subjects who did not receive ED chest imaging and 212 subjects with no thoracic injury on ED chest imaging. None of these subjects were diagnosed with injury at any later time.

The thoracic injury yields of CXR alone and chest CT after normal CXR were 8.4% (95% CI = 7.8% to 8.9%) and 15.0% (95% CI = 13.9% to 16.2%), respectively. The yield of CXR alone for thoracic injury with major clinical significance was 3.0% (95% CI = 2.7% to 3.3%) and for CT after normal CXR was 1.5% (95% CI = 1.2% to 2.0%; see Table 3 for other diagnostic yields).

The mean, median, and range of charges for CXR at the study sites were $323, $298, and $220 to $558, and the mean, median, and range of charges for trauma protocol chest CT were $3,052, $3,294, and $2,011 to $3,963. The mean, median, and range of ERD for trauma protocol chest CT were 8.9, 8, and 7 to 15 mSv, respectively. Table 4 has the mean charges and ERD of imaging tests per subject diagnosed with injury.

DISCUSSION

Like all other diagnostic tests, trauma imaging is not, of itself, therapeutic. The only patients who derive true, clear-cut benefits are those who are diagnosed with injuries that would not have been detected otherwise and, more specifically, those who are diagnosed with injuries that lead to therapeutic interventions or significant management changes. In this context, and considering the incremental utilization of trauma imaging (especially CT), we have defined the diagnostic yields, mean charges, and mean ERD per injury diagnosis of CXR, chest CT, and chest CT after normal CXR. We determined that, although the diagnostic yield of CT is higher than CXR, the charges and the ERD per injury diagnosed of CT (and especially CT after normal CXR) are markedly greater. These differences are magnified substantially when we consider the yields, charges, and ERD of CT (after normal CXR) to detect thoracic injuries with major clinical significance, such that mean charges and ERD exceed $200,000 and 590 mSv per diagnosis.

Our mean ERD of 8.9 mSv for chest CT closely approximates the median ERD of 8 mSv reported by Smith-Bindman and colleagues,[2] who estimated from

Table 3
Imaging Yields: Subjects With Findings on Imaging/Subjects Who Had That Imaging

Type of Imaging	Any Thoracic Injury Seen	Thoracic Injury With Major Clinical Significance	Thoracic Injury With Major or Minor Clinical Significance
CXR	8.4 (7.8–8.9)	3.0 (2.7–3.3)	8.2 (7.7–8.8)
Chest CT	28.8 (27.5–30.2)	6.9 (6.2–7.7)	27.2 (25.9–28.5)
Chest CT after normal CXR	15.0 (13.9–16.2)	1.5 (1.2–2.0)	14.4 (13.3–15.6)

Data reported as% (95% CI).

Table 4
Mean Charges and ERD per Injury Diagnosed

Type of Imaging	Charges for any Thoracic Injury Diagnosed	Charges for Thoracic Injury With Major Clinical Significance	ERD for Any Thoracic Injury Diagnosed	ERD for Thoracic Injury With Major Clinical Significance
CXR	3,845 (2,619–6,643)	10,767 (7,333–18,600)	0.24	0.67
Chest CT	10,597 (6,983–13,760)	44,232 (29,145–57,435)	30.9 (24.3–52.1)	129.0 (101.4–217.4)
Chest CT with normal CXR	20,347 (13,407–26,420)	203,467 (134,067–264,200)	59.3 (46.7–100)	593.3 (467–1,000)

Data reported as mean (range), with charges in US dollars, and dose in millisieverts
ERD = effective radiation dose.

the BEIR VII report that one radiation-induced cancer would result from every 720 forty-year-old female patients and every 1,538 forty-year-old male patients undergoing chest CT with contrast. Assuming similar cancer induction risk in our study population, whose median age was 45 years, the current imaging practice of chest CT after normal CXR may induce approximately one cancer for every 108 thoracic injuries diagnosed in women, one cancer for every 231 thoracic injuries diagnosed in men, one cancer for every 11 thoracic injuries of major clinical significance in women, and one cancer for every 23 thoracic injuries of major clinical significance in men.

Although the costs and yields of many treatment modalities have been reported (usually in terms of dollars per quality-adjusted life-year saved [QALY]), very few studies have examined the costs of diagnosis—and most of these have focused on the diagnosis of chronic conditions.[18,19] It is difficult to place chest CT in this context without introducing major assumptions about the costs and efficacy of acute trauma interventions and the morbidity associated with concomitant injuries, as well as the diagnostic yields and costs of work-up of incidental findings noted on CT. Nonetheless, we have demonstrated a high charge per injury diagnosis of trauma protocol chest CT, suggesting that formal cost-effective analyses of chest CT (and trauma imaging in general) are warranted.

Our results should not be viewed as discouragement against the use of chest CT in the evaluation of blunt trauma in adults, especially those critically ill patients with evidence of multisystem trauma. Chest CT is an important tool that aids in the rapid detection and definition of clinically important injuries.[20] Our primary focus of this line of research is on the less critically injured patient, in whom we hope to develop efficient, selective imaging guidelines that would maximize diagnostic yield while minimizing cost and radiation exposure. Toward this goal, we have identified three points in the assessment of blunt trauma patients that are most amenable to the development and implementation of chest imaging decision rules. The first point occurs at initial patient evaluation prior to the ordering of any CXR—identification of a group of patients who are at such low risk of injury that they do not need or benefit from any chest imaging at all. In two large, prospective, multicenter cohorts of blunt trauma patients, we derived and validated a simple rule consisting of readily available clinical criteria that defines this group of "very-low-risk" patients and allows for the safe omission of chest imaging in approximately 13% of patients who would otherwise receive it.[12]

We have shown that although initial trauma CXR misses many thoracic injuries, the diagnostic yield for clinically major injury of chest CT after normal CXR is very low, and the charges and radiation dose per injury diagnosed are very high. We therefore recommend a second useful point for the development of a chest imaging decision rule—guidance for selective chest CT in patients who have normal CXRs. Many authorities and centers have promoted and adopted protocols of whole-body CT (pan-scan) in polytrauma victims, and a selective chest CT decision rule must take into account the practi-
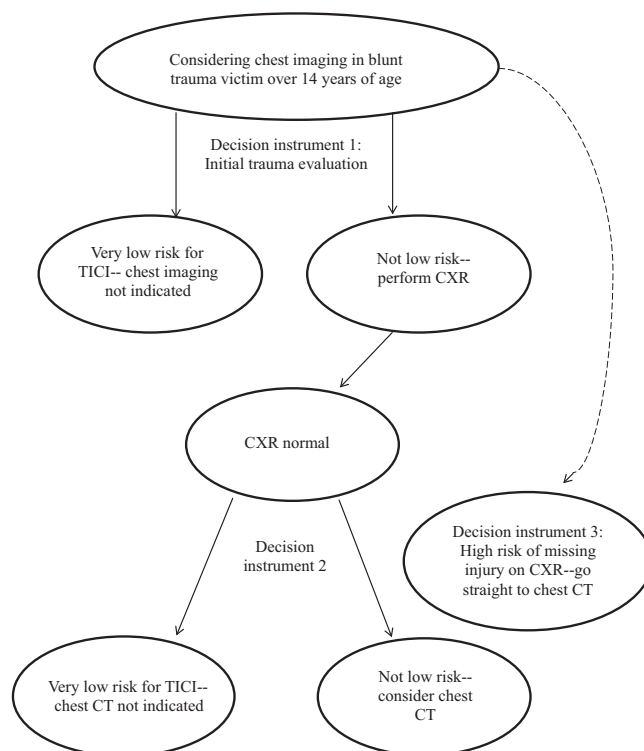

Figure 1. Proposed model for blunt trauma chest imaging decision instrument development. CT = computed tomography; CXR = chest x-ray; TICI = thoracic injury seen on chest imaging.

cal considerations of urgent patient evaluation without multiple trips to the CT scanner.[21,22] Nonetheless, we believe that a decision rule of simple criteria can rapidly and safely identify those non–critically injured patients who would benefit from omission of the chest CT portion of these pan-scans (patients who have normal CXRs and a very low risk of clinically significant thoracic injury). Pinette et al.[23] have noted that normal findings on CXR and abdominal CT are sufficient to rule out most significant thoracic injuries in blunt trauma patients, especially those who have minor trauma mechanisms.

A third possible decision rule target point would be defining a group of patients whose risk of significant injury missed on CXR is so high that they should forego plain CXR and have initial chest CT instead. Considering the low cost and radiation exposure of CXR, the potential resource savings from such a no CXR—straight to CT decision rule would likely be low. Furthermore, it would not apply to those patients who have other needs for immediate trauma CXR, such as verification of endotracheal tube position after intubation. Figure 1 demonstrates our summary proposal for the development of a blunt trauma chest imaging algorithm.

LIMITATIONS

Individual physicians may hold starkly contrasting views regarding the utility and need for trauma imaging and may disagree with our definitions of clinically major, minor, and insignificant injury.[24] Some practitioners may believe that it is important to diagnose all injuries at any cost (even those that do not alter patient

management) and that patients benefit from ruling out disease with negative imaging studies. It is likely that some patients have shorter ED and hospital stays as a result of negative advanced imaging, although the results reported by Korley et al.[7] may argue otherwise. Even if one considers the importance of ruling out injury, well-constructed and validated decision rules may safely accomplish this function without the cost and radiation of imaging studies.

Another limitation is verification bias, because less than half of subjects received chest CT—we may have missed thoracic injuries in subjects who only received CXR. While not eliminating this bias, our follow-up of patients with negative ED CXR argues that this bias is very limited in scope. Furthermore, our goal of this research was to address imaging overutilization as it may currently occur in real-world practice—not as it would occur on a theoretical, perfect-yield diagnostic imaging basis.

True costs of imaging are essentially unobtainable; our most significant limitation may be our use of charges as a surrogate parameter for costs to estimate the financial implications of trauma imaging. Charges are likely inflated, not accurately reflecting hospital costs or reimbursement. However, using cost-to-charge ratios from federal and state data sources, a commonly used economic analysis conversion technique that is endorsed by the U.S. Preventive Health Services Panel on Cost-Effectiveness Analysis and applying a low, conservative cost-to-charge ratio of 0.4, the costs per major injury diagnosis of CT ($17,693) and CT after normal CXR ($81,387) remain very high.[25] Similarly, our estimates of ERD may not accurately reflect the radiation dose delivered to individual patients.

We conducted this study at urban U.S. Level I trauma centers, and it is possible that evaluation of imaging at dissimilar hospitals might produce different diagnostic yields and charges for imaging. Although we did not enroll at all hours of the day, we compared enrolled subjects with a sample of potential subjects from nonenrollment hours and found them to have similar demographics and injury mechanisms (data not shown). Because trauma imaging protocols in children differ from those in adults, our yields and summary recommendations do not apply to the pediatric population.

CONCLUSIONS

Although chest computed tomography has greater diagnostic yield for thoracic injuries than chest radiography, it generates substantially higher charges and delivers a much greater effective radiation dose per injury diagnosed. Toward the goal of reducing unnecessary chest imaging in blunt trauma evaluation, the optimal points for selective chest imaging protocols and decision rule development that we identified are 1) at initial patient evaluation (identification of patients who are at such low risk of injury that they may forego all chest imaging); 2) when considering chest computed tomography after normal chest radiography (identifying patients who have very low potential for thoracic injury and clinically significant thoracic injury on subsequent chest computed tomography); and 3) at initial evaluation,

determination of patients who should skip CXR and go straight to chest computed tomography (high risk of clinically significant missed injury by chest radiography).

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