Article:
Howard, A orcid.org/0000-0001-7746-1268, West, R orcid.org/0000-0001-7305-3654, Iball, G et al. (3 more authors) (2019) An Estimation of Lifetime Fatal Carcinogenesis Risk Attributable to Radiation Exposure in the First Year Following Polytrauma: A Major Trauma Center's Experience Over 10 Years. Journal of Bone and Joint Surgery, American Volume, 101 (15). pp. 1375-1380. ISSN 0021-9355

https://doi.org/10.2106/JBJS.18.01334

Background:

The utilization of medical imaging continues to rise, including routine use in major trauma centers. The aims of this study were to estimate the amount of radiation exposure from radiographic imaging and the associated carcinogenesis risk among patients treated for polytrauma at 1 institution.

Methods:

Included were patients who were admitted to our institution with an Injury Severity Score (ISS) of ≥16 during the period of January 2007 to December 2016. Records of patients were reviewed to assess exposures to radiation (excluding any fluoroscopy) for 12 months following the initial admission. The risk of developing a fatal cancer of any type was modeled using patient age and sex, on the basis of the International Commission on Radiological Protection (ICRP) recommendations. Estimates of cancer risk were based on the exposure received and then imported into previously developed models.

Results:

Overall, 2,394 patients, with a mean ISS of 28.66 (range, 17 to 66), were included in our analysis. The mean total radiation dose received was 30.45 mSv and the median dose was 18.46 mSv. One hundred and fifteen patients (4.8% of the cohort) received ≥100 mSv of radiation. The total patient group had a 3.56% mean risk of fatal carcinogenesis of any type that related solely to medical exposure of radiation as a result of their injuries. In their lifetime, 85 patients would be expected to develop cancer as a result of medical imaging that they had undergone in the year following their accident. The ISS and the body region injured within the ISS were predictive of the level of radiation exposure.

Conclusions:

Those involved in trauma care can use the ISS and body region to predict radiation exposure and the risk of fatal carcinogenesis of any type. We found that, for injuries to the limb and pelvis, the greater the severity of injury, the greater the radiation exposure and fatal carcinogenesis risk. However, this study does not provide an actuarial analysis. It is unknown how many patients in the study went on to develop cancer.

Level of Evidence:

Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

The utilization of medical imaging continues to rise. In the U.S., in 2004, about 62 million computed tomography (CT) scans were performed, compared with 3 million in 1980[1]. Interestingly, diagnostic imaging has become the largest man-made source of radiation exposure, totaling 14% of the total annual exposure worldwide from all sources[2].

Associating the degree of radiation exposure with the risk of carcinogenesis has been a point of ongoing discussion. For instance, the act of flying to New York from London exposes the traveler to 0.1 mSv, while working in the International Space Station annually exposes the astronauts to 170 mSv, whereas annual exposure to background radiation from living in the U.S. is 3 mSv and, in the U.K., is 2 mSv[3]. Regulations in the U.K. draw a distinction between occupational and general exposure, for the latter, recommending that annual exposure be limited to 20 mSv[4]. There is reasonable evidence that acute exposure at a dose of >5 mSv increases the risk of some cancers and good evidence that exposure of >50 mSv increases the carcinogenesis risk[5]. There is significant risk for acute and chronic exposures, particularly in doses of >100 mSv[3].

With regard to medical imaging, it is believed that, as exposure to x-rays through diagnostic imaging increases, so does the risk of cancers[2]. Of interest, in 1981, 0.5% of U.S. cancer deaths were attributable to diagnostic radiographs[6], whereas in 2004, this estimate had increased to 1.8%[2]. Previous studies have identified cohorts of patient who are at increased risk of developing breast cancer due to a clinical condition that necessitates frequent radiographic investigations; these include conditions such as tuberculosis and scoliosis[7]. Of note, there has been no previous analysis, to our knowledge, of the site-specific radiation exposure among patients with multiple injuries (polytrauma) and the associated risk of fatal carcinogenesis of any type[8]. The risk of carcinogenesis falls with age; those involved in polytrauma are often younger and the risk is thus greater[9]. In the U.K., it has been estimated that approximately 25,000 patients per year sustain polytrauma[10]. Moreover, with the implementation of regional major trauma centers (MTCs) and more lives saved annually, a higher number of patients are exposed to potentially hazardous radiation.

We had 3 aims with the current work: (1) to estimate the level of radiation exposure experienced by the patients at our institution; (2) on the basis of the known radiation exposure, to model the level of risk for developing a fatal solid tumor; and (3) to investigate which injuries were associated with higher levels of radiation exposure and thus placed the patient at increased risk of fatal carcinogenesis of any type.

Materials and Methods

A request was made to the Trauma Audit & Research Network (TARN) for the records of patients with an Injury

Severity Score (ISS) of ≥16 who were treated by the Leeds MTC, England, during the period of January 2007 to December 2016. The ISS (based on 6 body regions) is a medical score used to assess trauma severity, corresponding to mortality and morbidity of the injuries[5]. The ISS is the sum of squares of the highest Abbreviated Injury Scale (AIS) score in each of the 3 mostly severely injured body regions (Table I). The most severely injured 3 regions are given a score of 0 to 6 (0 = no injury, 1 = minor, and 6 = maximal [currently untreatable]); these values, up to a maximal value of 5, are each squared and added together to make a score of 0 to 75. The AIS scoring system was issued by the Association for the Advancement of Automotive Medicine[11], and injuries are scored within the regions of the ISS according to severity (Table I). The definition of polytrauma is an ISS of ≥16[12]; patients with isolated injuries who had an ISS of ≥16 were excluded. Patients who died within 30 days of the index traumatic event were also excluded. Our institute's Research and Development Department concluded that this work could be undertaken as a service evaluation; formal ethical approval was not required.

Different human tissue has different sensitivity to radiation exposure, which translates into different risks of carcinogenesis as a result of that exposure. All doses of radiation exposure were converted to millisieverts (mSv) by an established factor to take into account the differing sensitivity/risk according to the type of tissue. Shrimpton et al.[13] coefficients were adopted for the CT doses in which the dose-length product (DLP) was known ("acute dose"). For radiographic assessments (radiograph or CT) for which the DLP was not known, accepted values for the identical body tissue were used[14] ("predicted dose"). As all of the doses of radiation were converted to mSv, this represents the effective dose received by the patient, taking into account tissue sensitivity, thus enabling interpatient comparison and the calculation of the risk of fatal carcinogenesis of any type[15].

The Leeds MTC picture archiving and communication system (PACS) was queried according to the patient details provided by TARN, and the number, doses, and type of radiographic examinations received in the year following the patient's accident were recorded. Dose records from the image intensifier systems in the operating theaters for fracture fixation and for cardiovascular investigation were unreliable and therefore were excluded. When values were absent, published radiation doses were used as a broad estimate of doses that would have been used locally[8,14,16,17], a recognized technique[18-20]. To test the validity of the estimated doses, for the assessments for which an actual dose was known (n = 21,827), a comparison with the predicted dose was made (Fig. 1), which demonstrated a Pearson correlation of 0.47 ($p < 0.01$).

The risk of fatal carcinogenesis of any type was calculated, taking in account the sex and age of the patient, as the risk of carcinogenesis is dependent on sex and age[6,21-24]. No patients were

followed as part of this study. The calculated risk represents an additional risk as a result of the exposure to radiation for medical investigations and is separate from patient-related risk factors, such as previous cancer diagnosis, environmental exposure, smoking, and genotype. The radiation risk models used for medical radiographic examinations that were developed by the International Commission on Radiological Protection (ICRP) have been evaluated as a function of the age and sex of the patient[21,24]. Wall et al. further developed these models into lifetime risk of cancer by age and sex for all cancers[9]. This model was applied to the exposure experienced by the patient group.

Statistical Analysis

A generalized additive model, a standard nonlinear regression model, was created to use both the regions and the severity score of those regions as predictive variables for the level of radiation exposure and thus the risk of carcinogenesis. To examine the relationship between ISS and radiation dose, dose was regressed upon ISS. To enable a nonlinear relationship, a generalized additive term was applied, and splines were used to fit the curve. In addition to the ISS, the model was extended to permit the use of the AIS score for each region as a covariate.

Results

Overall, 2,462 patients with an ISS of ≥16 met the inclusion criteria. Sixty-eight patients died within 30 days of admission and were excluded. Consequently, 2,394 patients were included in our analysis. Information pertaining to radiation dose was available for 57% (21,827) of the radiographic assessments. When values were absent (16,668 assessments), published radiation doses were used as a broad estimate of doses that would have been used locally[8,14,16,17], a recognized technique[18-20].

This patient group had a mean age of 43.03 years (range, 0.6 to 99.2 years) and underwent 38,495 radiographic assessments (12,600 CT evaluations and 25,895 radiographs). The mean ISS was 28.66 (range, 16 to 66). The mean number of radiographs per patient was 10.82 (range, 1 to 172), and the mean number of CT evaluations was 5.26 (range, 1 to 96).

For this patient cohort, the mean and median radiation doses received in the 12 months following injury were 30.45 mSv and 18.46 mSv, respectively. The mean dose from CT was 25.64 mSv and from radiographs, was 4.81 mSv. Of the 2,394 patients, 115 (4.8%) received ≥100 mSv of radiation within 12 months of the index accident (mean dose, 158.82 mSv [range, 100 to 292 mSv]). In this group of patients whose exposure was >100 mSv, the mean ISS was 32.16 (range, 16 to 66) and the mean age was 34.3 years (range, 0.6 to 99.2 years). The mechanism of injuries for the majority of this group was road traffic collisions (53.8%), with the mechanism for the remaining patients including a fall from >2 m (19.7%), stabbing (3.4%), and crushing (12%). For the patients

who received <100 mSv, the mechanism of injuries related to road traffic collisions was marginally greater, 55.29%. The mean ISS was 31.89 (range, 16 to 66), and the mean age was 35.7 years. The 2 groups did not differ significantly with respect to age, mechanism, and ISS ($p \geq 0.05$).

The median additional lifetime risk of fatal carcinogenesis for the total group was 3.43%; the mean risk was 3.56%. Thus, in the group of 2,394 patients, 85 patients would be expected to develop cancer within their lifetime as a result of medical imaging in the year following their accident. Given the variation of cumulative radiation dose and the number of radiographic assessments, the patients exposed to the highest levels of radiation were removed and a sensitivity analysis was undertaken for patients who received a total of ≤75 mSv (2,180 patients); the change was negligible, with a slightly lower effect, which is to be expected given that the higher values had been removed. The patient groups were matched by age, sex, and ISS across lower radiation ranges (0 to 25, 26 to 50, and 51 to 75 mSv) to model the exposure levels and the risk of fatal carcinogenesis of any type (Table II). The average exposure in the 3 groups increased as expected; however, the risk was not significantly different, ranging from 2.84% to 4%.

When the global ISS score was used as a predictive variable for radiation exposure (Fig. 2), there was a linear relationship up to an ISS of 50 (2,226 patients [93.0%] of the patient cohort had an ISS of ≤50) and then a downward trend, with increasing confidence intervals. This could have been influenced by patients with an ISS of >50 not surviving 12 months following their accident, but mortality data were incomplete. To assess the secular trends in the variation in the number of images made over time (at 2 set points, 2007 [start] and 2016 [end]) and deaths within 30 days of admission, these were added to the model as plausible covariates, and there was no significant difference.

We then used the AIS regions as predictors of dose exposure. The multiple nonlinear regression, generalized additive model showed an associative effect for the thorax, abdomen, spine, pelvis, and limbs (Fig. 3), i.e., we observed the associative effect of AIS score within the body regions and the relationship of that predictive effect on the cumulative radiation exposure within the first 12 months post-accident, as the AIS score increased. There was a linear relationship for pelvis and limbs, whereas there was a peak and then a drop-off of the associative effect for the thorax, abdomen, and spine. No individual injuries where predictive of either radiation exposure or the risk of fatal carcinogenesis of any type.

Discussion

In our overall cohort of patients, exposure of ≥100 mSv was noted for 115 patients. For the complete cohort, the mean exposure for the year following injury was 30.45 mSv, which is

not unsubstantial when compared with the 2 mSv annually from background radiation in the U.K[3]. To put this in context, the cumulative effective dose for a typical CT scan of the chest, abdomen, and pelvis in the U.K. is 20 mSv[14]. There is evidence that acute exposure at a dose of >5 mSv increases carcinogenesis risk, with the risk increasing dramatically when >50 mSv[5].

Research into the safe level of radiation has, in the main, been extrapolated from survivors of the Chernobyl and Three Mile Island industrial accidents and from the nuclear attacks on Hiroshima and Nagasaki. In terms of use within the medical context, the advice is broadly "that radiological investigations should be used when clinically justified,"[25,26] and that the radiation doses used should be as low as reasonably practicable consistent with the intended purpose of the examination[27]. In recent work by Sierink et al. in which total-body CT scanning was compared with conventional imaging and selective CT scanning in a trauma setting, no difference in mortality between the 2 types of assessments was found[28].

We found that, for polytrauma patients, the median risk of developing a fatal solid tumor as a result of medical radiation in the 12 months following injury was 3.43%. This is an important additional risk that patients need to understand as they progress through the treatment of their injuries. Currently, we warn patients of the risks or complications of surgery even if the chances of their occurrence is low but the impact is of concern[29]. There is no agreement as to a threshold percentage above which patients should be told of the risk[28]. The control group matched by age, sex, and ISS (Table II) demonstrated a lower level of risk overall for a cumulative radiation exposure of ≤75 mSv compared with the median of the total group, with the mean risk by sex in the control group ranging from 2.91% to 4% for male patients and 2.84% to 3.64% for female patients. It should be noted that the average age difference between male (28 years) and female (42 years) prohibits a meaningful comparison on the basis of sex. The risk of developing a fatal cancer in the general population in the U.S. is 22.03% in males and 18.76% in females[30].

In patients with an ISS value of ≤50, the ISS may be useful in identifying which patient should be monitored because of their cumulative radiation exposure in the year following injury; radiation dose is often recorded routinely.

In terms of body regions that make up the ISS, an AIS score of ≤3 was predictive for the spine, abdomen, and thorax, i.e., the greater the AIS score, the greater the patient's radiation exposure, up to an AIS score of 3. For the pelvic and limb regions, the predictive value was linear up to an AIS score of 5. Thus, for pelvic and limb injuries, the greater the severity of injury, the great the radiation exposure and risk of fatal carcinogenesis of any type. In contrast, for injuries of the spine, abdomen, and thorax, the exposure and risk were lower for the more severely injured patients. However, there are many other factors that will influence

radiation exposure, such as the clinicians' decisions regarding the type and volume of radiographic imaging. Furthermore, monitoring could be undertaken as part of patient follow-up before and after discharge from the hospital, with extraction of the data by the clinician from the radiology information systems.

Study Limitations

Only the risk of fatal carcinogenesis of any type was addressed; there are many types of cancer with different sensitivities to radiation exposure. Furthermore, our study looked at the generalized risk of carcinogenesis rather than organ-specific or actual occurrence; however, if patients were followed to establish actual occurrence, the large number of confounding factors would make causation impossible to safely conclude. Forty-three percent of the values were estimated rather than the actual values of radiation exposure. This has the potential to have biased the study, as the values may either under- or overestimate radiation exposure.

This was a single-center study and did not capture assessments that may have occurred among patients after repatriation to other hospitals. However, we estimate this would have applied to <100 patients. Furthermore, the results are only translatable to other centers if they operate with protocols similar to those at our own center. Another limitation of our study is that it represents an underestimation of the total radiation exposure and, therefore, the risk, as exposure from fluoroscopy was not included because the dose data were unavailable. For example, if a patient underwent the insertion of a metal nail into the femur, the radiation exposure from fluoroscopy would be roughly 1 mSv[21]. In polytrauma, patients undergo many surgical procedures of a similar nature, if not greater magnitude, in the 12 months following injury, and thus, this underestimation of dose and risk is not unsubstantial. In addition, because of how data were collected at our institution, we cannot identify patients who died between 30 days and 12 months of their accident, so this may have resulted in underestimation. The paradoxical decrease in some radiation exposures with increased AIS scores (Figs. 2 and 3) may be explained by the fact that these patients did not survive beyond 30 days.

Conclusions

A high number of patients with polytrauma are exposed to high levels of radiation in the year following injury, and the additional risk of fatal carcinogenesis of any type is not unsubstantial. Clinicians can reduce this risk by using non-radiographic assessments or reduce exposure by detailing instructions for radiographic assessments that reduce radiation by specifying exact areas of interest or deploying alternate modalities such as ultrasound or magnetic resonance imaging.

Patients with injuries that are predictive of high levels of radiation exposure should be given additional warning over and above the general warning regarding the risk of radiation exposure. Clinicians may assess the level of cumulative exposure either by accessing the radiographic system themselves or having the data provided to them. No individual injuries where predictive of either radiation exposure or the risk of developing a fatal solid tumor.

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Fig. 1

Comparison of the actual and predicted doses for radiographic examinations (radiographs and CT) undertaken from 2007 through 2016 (n = 18,446).

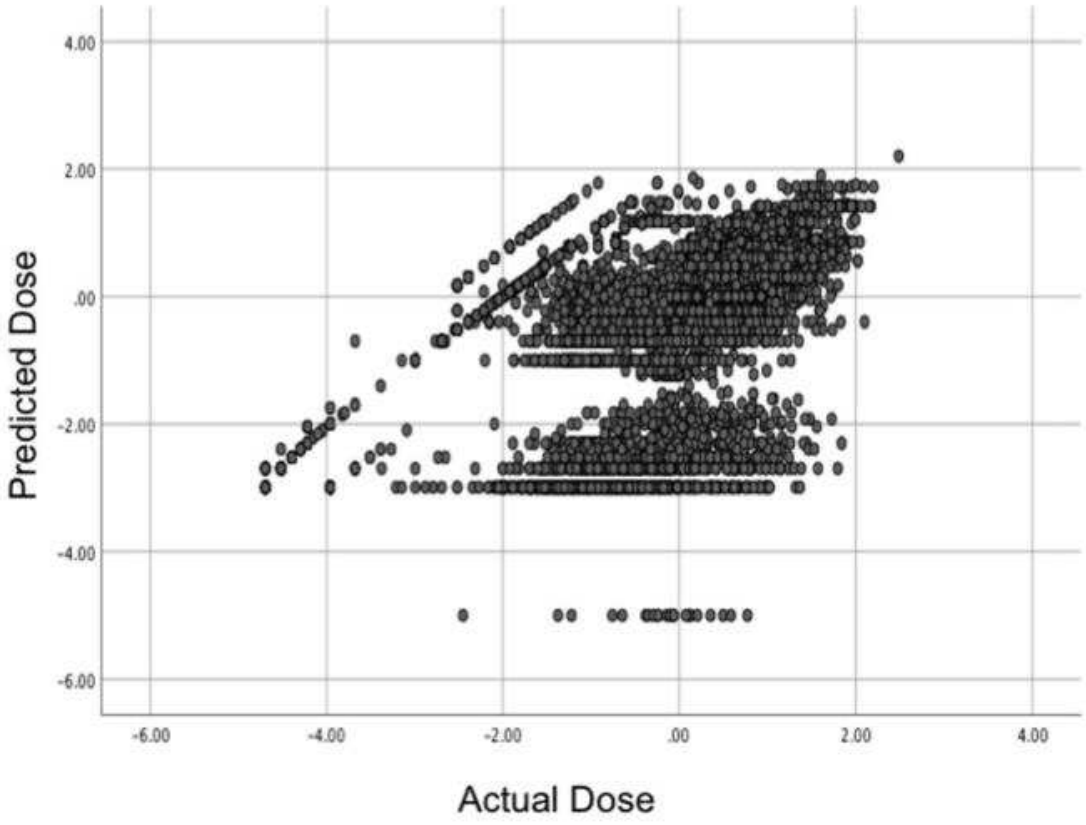


Fig. 2

Graph showing the effect of the Injury Severity Score (ISS) on patient radiographic radiation exposure(s) versus the ISS. The solid line indicates the mean, and the dashed lines indicate the 95% confidence interval.

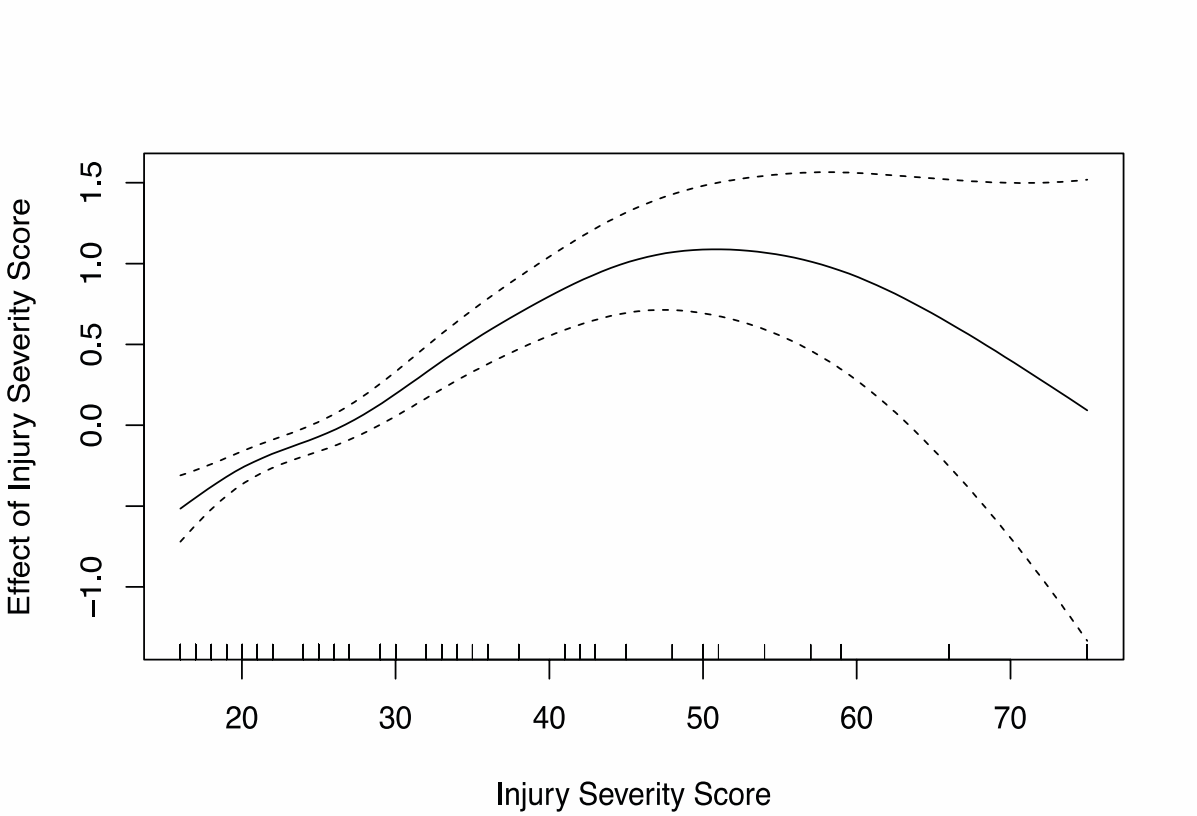
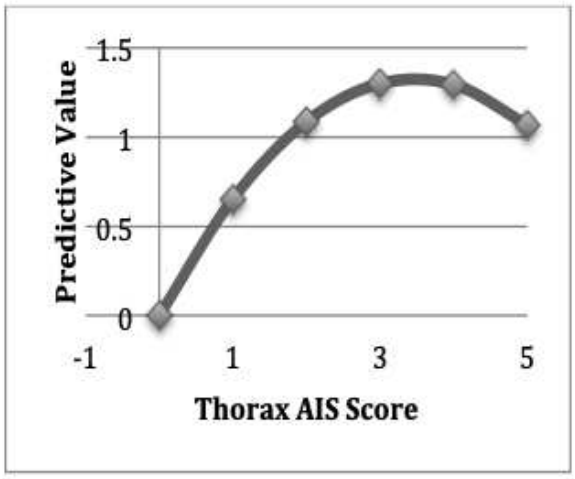
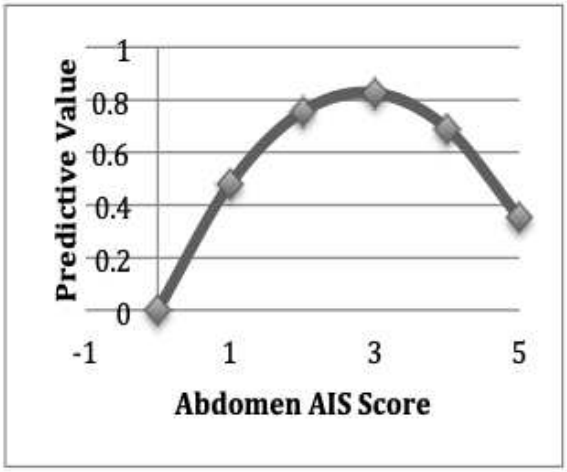
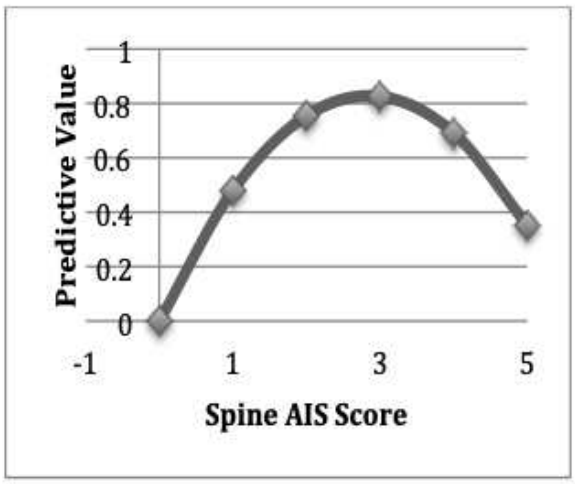


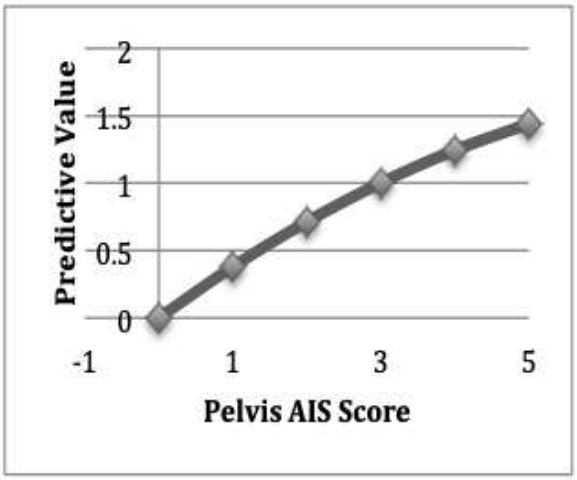
Fig. 3

Results of multiple linear regression showing the predictive effect of the Abbreviated Injury Scale (AIS) score for the thoracic, abdominal, spinal, pelvic, and limb regions.









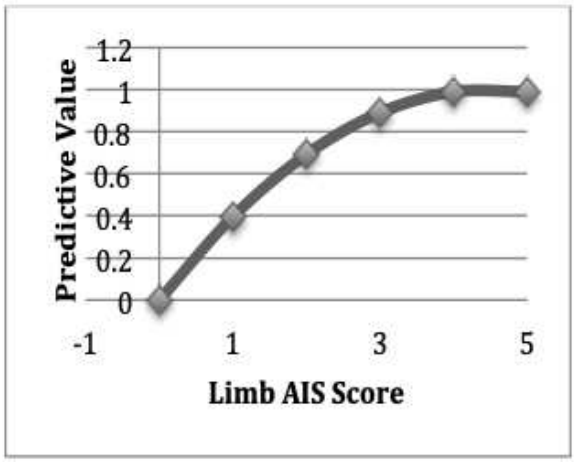


TABLE I Examples of Injuries by Abbreviated Injury Scale (AIS) Region and Increasing Injury Severity Score (ISS)

	AIS Score	Thorax	Abdomen	Spine/Head	Pelvis	Limb
Minor	1	Rib fractures, 3-4 ribs	Vagus nerve injury	Spinous ligament injury	Testes contusion	Knee sprain
Moderate	2	Pneumothorax	Retroperitoneal hematoma	Unconscious <15 min, no fractures, no signs of	Acetabular fracture	Fibular fracture

				neurological injury		
Serious	3	Hemopneumothorax	Laceration of the vena cava	Subarachnoid hemorrhage	Open stable pelvic ring fracture	Femoral fracture
Severe	4	Flail chest, >5 ribs	Major liver laceration	Cerebral contusions, internal carotid transection	Open unstable pelvic ring fracture	Amputation at the shoulder level
Critical	5	Herniation of the heart through the pericardium	Penetrating injury, >20% blood loss	Complete cord syndrome, quadriplegia	Pelvic ring fracture with >20% blood loss	Bilateral above-the-knee amputation

TABLE II Age-Matched Patients by Level of Radiation Exposure*

	0-25 mSv		26-50 mSv		51-75 mSv	
	Male	Female	Male	Female	Male	Female
Average exposure *(mSv)*	17.33	6.62	33.92	37.86	60.90	58.51
Average risk of carcinogenesis *(%)*	4.00	3.64	3.33	2.84	2.91	3.02
Average ISS	33.53	29.38	33.85	29.41	33.98	29.38
Average age *(yr)*	28	42	28	42	28	42

*The male-to-female ratio was 5:1 in the 0-25 mSv group, 5.67:1 in the 26-50 mSv group, and 4.85:1 in the 51-75 mSv group.