Is radiography justified for the evaluation of patients presenting with cervical spine trauma?

Nicholas Theocharopoulos
Department of Medical Physics, Faculty of Medicine, University of Crete, P.O. Box 2208, Iraklion, 71003 Crete, Greece and Department of Natural Sciences, Technological Education Institute of Crete, P.O. Box 140, Iraklion 71004 Crete, Greece

Georgios Chatzakis
Department of Radiology, Faculty of Medicine, University of Crete, P.O. Box 2208, Iraklion, 71003 Crete, Greece

John Damilakis[a)]
Department of Medical Physics, Faculty of Medicine, University of Crete, P.O. Box 2208, Iraklion, 71003 Crete, Greece

(Received 26 April 2009; revised 4 July 2009; accepted for publication 30 July 2009; published 8 September 2009)

Conventional radiography has been for decades the standard method of evaluation for cervical spine trauma patients. However, currently available helical multidetector CT scanners allow multiplanar reconstruction of images, leading to increased diagnostic accuracy. The purpose of this study was to determine the relative benefit/risk ratio between cervical spine CT and cervical spine radiography and between cervical spine CT and cervical spine radiography, followed by CT as an adjunct for positive findings. A decision analysis model for the determination of the optimum imaging technique was developed. The sensitivity and specificity of CT and radiography were obtained by dedicated meta-analysis. Lifetime attributable risk of mortal cancer from CT and radiography was calculated using updated organ-specific risk coefficients and organ-absorbed doses. Patient organ doses from radiography were calculated using Monte Carlo techniques, simulated exposures performed on an anthropomorphic phantom, and thermoluminescence dosimetry. A prospective patient study was performed regarding helical CT scans of the cervical spine. Patient doses were calculated based on the dose-length-product values and Monte Carlo-based CT dosimetry software program. Three groups of patient risk for cervical spine fracture were incorporated in the decision model on the basis of hypothetical trauma mechanism and clinical findings. Radiation effects were assessed separately for males and females for four age groups (20, 40, 60, and 80 yr old). Effective dose from radiography amounts to 0.050 mSv and from a typical CT scan to 3.8 mSv. The use of CT in a hypothetical cohort of 10^6 patients prevents approximately 130 incidents of paralysis in the low risk group (*a priori* fracture probability of 0.5%), 500 in the moderate risk group (*a priori* fracture probability of 2%), and 5100 in the high risk group (*a priori* fracture probability of 20%). The expense of this CT-based prevention is 15–32 additional radiogenic lethal cancer incidents. According to the decision model calculations, the use of CT is more favorable over the use of radiography alone or radiography with CT by a factor of 13, for low risk 20 yr old patients, to a factor of 23, for high risk patients younger than 80 yr old. The radiography/CT imaging strategy slightly outperforms plain radiography for high and moderate risk patients. Regardless of the patient age, sex, and fracture risk, the higher diagnostic accuracy obtained by the CT examination counterbalances the increase in dose compared to plain radiography or radiography followed by CT only for positive radiographs and renders CT utilization justified and the radiographic screening redundant. © *2009 American Association of Physicists in Medicine*. [DOI: 10.1118/1.3213521]

Key words: CT, radiography, cervical spine, trauma, decision analysis

I. INTRODUCTION

There is a universal agreement for the necessity of imaging for the clearance of patients who have sustained traumatic injury of the cervical spine (CS) but the selection of the optimal imaging modality remains controversial over the years. The emergency medicine physician and the orthopedic surgeon are very often in a dilemma over the appropriate imaging study which will help direct treatment and improve outcome. Traditionally, plain radiography (three or five views), followed by CT as an adjunct, has been the imaging approach of choice.[1–3]

The wide availability of modern multidetector CT (MDCT) scanners currently offers rapid and accurate clearance of trauma patients, allow accurate multiplanar reformations, and can obviate the need for plain radiographs. Therefore, nowadays, MDCT may hold the role the single examination for the investigation of the CS trauma, which does not necessitate further imaging.[4] However, CT exami-

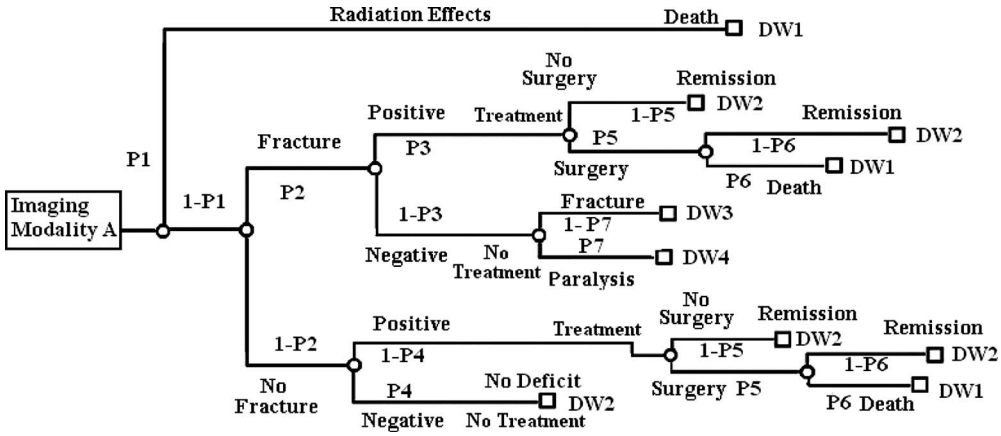

FIG. 1. Decision model for single-modality imaging policy (imaging modality A) showing treatment policies and outcomes and the associated DWs and probabilities (P).

nations are associated with a relatively high dose to the patient compared to conventional radiography and therefore bare the potential of late radiation effects such as leukemia and solid cancers. Hence, CT utilization is justified when the benefit (diagnostic accuracy) over risk (radiation effects) ratio is higher compared to other available imaging modalities.

Although recent epidemiological studies have revived the concern over the long term carcinogenic effects of ionizing radiation[5,6] no data exist in literature on the effectiveness of radiography and CT performed in cervical spine trauma patients in terms of radiation dose and risks. The aim of this study was to develop and apply a decision analysis model,[7,8] incorporating both expected health benefit and potential detriment from the two imaging modalities for the investigation of the radiation effectiveness of CT relative to radiography and the subsequent justification of CT usage for CS evaluation in trauma patients.

II. MATERIALS AND METHODS

II.A. Decision analysis

For the determination of the optimum imaging technique, we have performed decision analysis based on probability and Bayesian algebra.[9] Three imaging policies were considered: (a) Radiography, (b) MDCT, and (c) radiography followed by CT as an adjunct for positive findings. A positive diagnosis following radiography alone, CT alone, or CT as an adjunct for positive radiography was supposed to be followed by a surgical or nonsurgical intervention (surgical or mechanical stabilization) and postoperative mortality was also accounted for. The major complication following a false negative diagnosis was considered to be paralysis. Other possible health outcomes included radiogenic lethal cancer (solid cancer and leukemia). Every final health state (remission, paralysis, fracture, and death) was assigned with a disability weight (DW). The disease-specific disability weights have been introduced by national and international health organizations in order to quantify the merit of a health state and vary from 0 for perfect health to 1 for death. In a decision model, the disability weight of a final health state is multiplied by the probability of that state to occur given a decision is taken (policy) to yield the total disability of the policy. The effectiveness of a policy is inversely proportional to the corresponding total disability value.

Figure 1 illustrates the decision model for a single-modality imaging policy and the associated DWs and probabilities (P). For the imaging modality A, the total disability TD_A will be given by the following equation:

$$\begin{aligned}\mathrm{TD}_A = {} & \mathrm{DW1}\cdot[P1] + \mathrm{DW2}\cdot[(1-P5)\cdot P3\cdot P2\cdot(1-P1)] + \mathrm{DW2}\cdot[(1-P6)\cdot P5\cdot P3\cdot P2\cdot(1-P1)] \\ & + \mathrm{DW1}\cdot[P6\cdot P5\cdot P3\cdot P2\cdot(1-P1)] + \mathrm{DW3}\cdot[(1-P7)\cdot(1-P3)\cdot P2\cdot(1-P1)] + \mathrm{DW4}\cdot[P7\cdot(1-P3)\cdot P2\cdot(1 \\ & -P1)] + \mathrm{DW2}\cdot[(1-P5)\cdot P4\cdot(1-P2)\cdot(1-P1)] + \mathrm{DW2}\cdot[(1-P6)\cdot P5\cdot P4\cdot(1-P2)\cdot(1-P1)] \\ & + \mathrm{DW1}\cdot[P6\cdot P5\cdot P4\cdot(1-P2)\cdot(1-P1)] + \mathrm{DW2}\cdot[(1-P4)\cdot(1-P2)\cdot(1-P1)], \end{aligned} \tag{1}$$

where DW1 is the disability weight for death, DW2 is the disability weight for perfect health, DW3 is the disability weight for cervical spine fracture, DW4 is the disability weight for paralysis due to cervical spine fracture, $P6$ is the mortality associated with cervical spine surgery, $P5$ is the probability of cervical spine surgery following a positive cervical spine fracture diagnosis, $P7$ is the probability of paralysis following a missed cervical spine fracture, $P4$ is the

TABLE I. Health states and corresponding DWs associated with CS trauma.

Health state	DW	Reference
CS fracture	0.44	9
Paralysis due to CS fracture	0.30	15
Death	1	Definition
Remission	0	Definition

specificity of the imaging modality A, $P3$ is the sensitivity of the imaging modality A, $P2$ is the *a priori* fracture probability (prevalence or patient risk), and $P1$ is the radiogenic death probability (radiogenic risk).

Among the variables incorporated in the present study decision algorithm, the probability values regarding the prevalence of CS fracture, the treatment policy, and the postoperative mortality rates were obtained from the literature. Other determinants of the decision model were the diagnostic accuracy of imaging and the radiogenic risk.

II.B. Literature review and meta-analysis

The optimum imaging policy, as derived by the decision model calculations, is strongly dependent on the sensitivity and specificity of the imaging modalities under comparison. Hence, in order to determine the diagnostic accuracy of radiography and CT, we have performed dedicated literature review and meta-analysis. Literature clearance was conducted by two independent reviewers who screened the publication pool for potentially relevant articles. Disagreements in the selection of suitable publications were solved by discussion. Statistical analysis was performed using the META-DISC software program.[10] A detailed description of the literature search is provided in the Appendix.

II.C. Radiogenic risk evaluation and dosimetry

Lifetime attributable risk of mortal solid cancer and leukemia was calculated using Tables 12D-1 and 12D-2 of the BEIR VII report,[11] previously published methodology,[12] and organ-absorbed doses obtained by means of Monte Carlo techniques.

Patient organ doses from three-view radiography [anterior-posterior (AP), lateral (LAT), and odontoid view] were calculated using the Monte Carlo *N*-particle code (MCNP4C2, Los Alamos National Laboratory, Los Alamos, NM). Human anatomy was replicated by a mathematical phantom constructed with a commercially available software tool (BodyBuilder, White Rock Science, NM).

Projection-specific dose values were calculated by the Monte Carlo simulations on the basis of tube high voltage and filtration and were normalized over the amount of radiation incident upon the patient at the beam entry surface. This radiation quantity is called entrance surface dose (ESD), and it is measured using thermoluminescent dosimeters attached to the examinee's skin during the exposure.[13]

For the measurement of ESD, the radiographic projections were simulated on an anthropomorphic phantom (Rando phantom, Alderson Research Laboratories, Stamford, CT). The Rando phantom simulates the head and torso of an adult with height of 1.73 m and weight of 74 kg and consists of tissue equivalent material over a synthetic human skeleton. It has been widely used for dosimetric measurements in diagnostic radiology.[13] The radiographic exposures of the phantom were performed on a Siemens Polydoros 50 x-ray unit (Siemens, Erlangen, Germany). It is a conventional screen-film x-ray unit with a total filtration of 3.5 mm aluminum. The phantom was positioned erect against the vertical Bucky table and the focus to film distance was set to 110 cm for all projections. The AP and LAT radiographs were performed at 40 kVp, as used routinely for AP and LAT radiography in our institution, and 40 m As. A high voltage of 60 kVp and a tube load of 45 m As were applied for the odontoid projection. Lithium fluoride thermoluminescence dosimeters (TLD-100, Harshaw, OH) were used for recording the ESD resulting from the simulated examinations.

For the determination of patient doses from helical CT scans of the CS, we have performed an 8-month prospective study on an MDCT scanner (Sensation 16, Siemens, Erlangen, Germany) which included alert, low, and moderate risk trauma patients referred for CT evaluation. The helical scans of the cervical spine were performed at 120 kVp, a pitch value of 0.62, and reconstructed slice thickness of 0.75 mm. The prospective study was approved by the ethics committee of our institution. Patient consent was not required since the study did not alter the routine imaging management of trauma patients. For each patient in the prospective study, organ doses and effective dose from the helical scan were calculated based on the dose-length-product (DLP) values provided on a special card of the patient's record in the patient database of the CT operating console. Scanner-specific DLP to organ dose conversion coefficients were derived for both sexes using a Monte Carlo-based CT dosimetry software program.[14]

TABLE II. Probability ranges and adopted values for the decision model variables.

Variable	Probability (%)	Reference	Model values
Fracture probability	0.04–19.7	16	High risk 20%, moderate risk 2%, low risk 0.5%
Surgical intervention probability	5.2–32.9	17	24.6% adults, 7% geriatric (age ≥ 65 yr)
Mortality following surgery	0–16.7	18	1.6%, 12.2% geriatric (age ≥ 65 yr)
Paralysis following missed CS fracture	0–30	19–24	5%

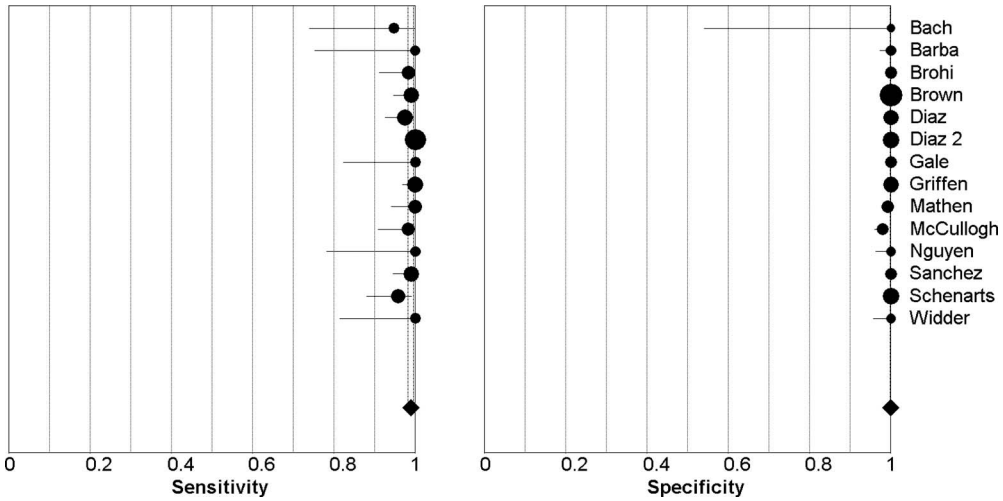

FIG. 2. Forrest plots for CT.

III. RESULTS

III.A. Variables for the decision model

Table I shows the disability weights[9,15] of the health outcomes associated with CS trauma. The value range of the variables required for the decision model is provided in Table II. The *a priori* probability of fracture depends largely on the patient age and mechanism of trauma.[16] Three values of fracture prevalence were considered in our model: 0.5% (low), 2% (moderate), and 20% (high). The method of fracture treatment and the prognosis depend on the patient age, severity of trauma, and neurologic findings.[17–24] In order to account for the differences in patient management and radiosensitivity with age, four age groups were distinctively examined in our model (20, 40, 60 and 80 yr old).

III.B. Literature review and meta-analysis

The initial literature search returned 212 articles. Title and abstract clearance was conducted and 140 papers were excluded from the study. Detailed reading of the remaining papers further excluded 20 articles. From the remaining 52 articles, 39 were excluded due to incomplete or irrelevant information. Complementary manual search yielded three additional articles for inclusion. Overall, 16 articles were included in our meta-analysis.[4,25–39]

Figures 2 and 3 demonstrate the Forrest plots for sensitivity and specificity for each modality. Sensitivity for CT ranged from 98% to 99% and for radiography ranged from 25% to 93%. Specificity was 100% for CT and ranged for radiography from 99% to 100%. Pooled sensitivity was 99% (95% CI: 98%–99%) and pooled specificity was 100% (95% CI: 100%–100%) for CT. Pooled sensitivity was 42.8% (95% CI: 39%–46%) and pooled specificity was 99% (95% CI: 99%–100%) for radiography. The derived values were used for the decision model calculations regarding CT. Because of the heterogeneity in the sensitivity and the specificity of radiography, the analysis was repeated with three studies included for the determination of sensitivity[4,25,28] and two[4,29] for the determination of specificity. Recalculated sensitivity was 48.3% (95% CI: 41.4%–55.3%, chi-square: 2.02, and $p=0.365$) and specificity was 98% (95% CI: 95.4%–99.4%,

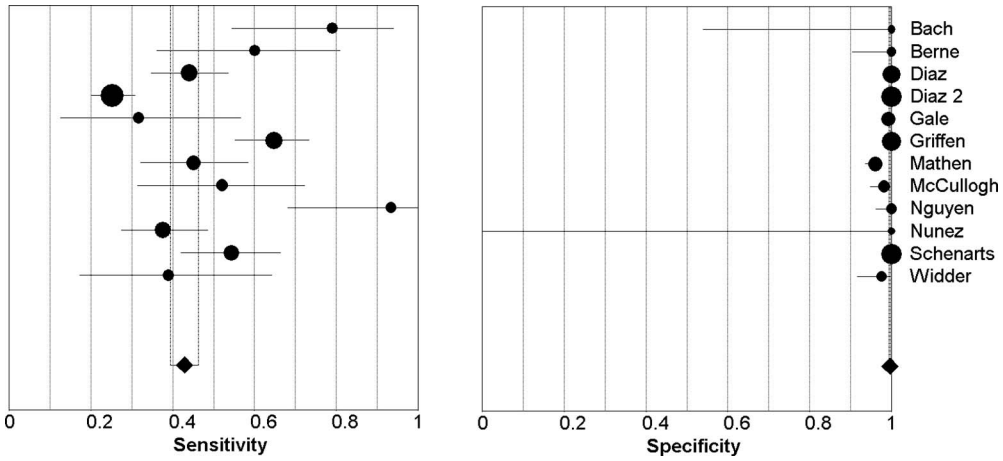

FIG. 3. Forrest plots for radiography.

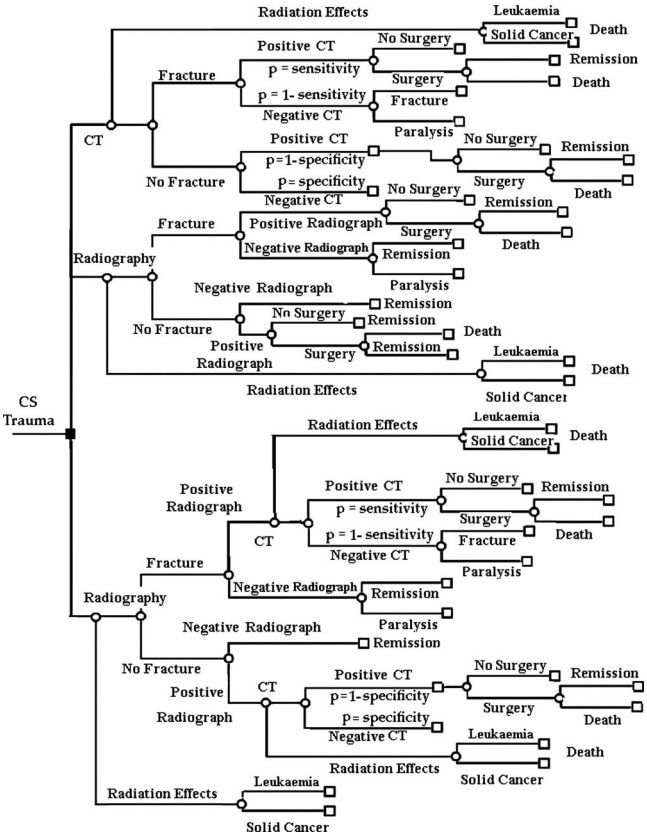

FIG. 4. Decision analysis model showing the three imaging options under comparison, treatment policies, and outcomes. The relationship between true positive, true negative, false positive, and false negative diagnosis and the sensitivity/specificity of the imaging modalities is also shown.

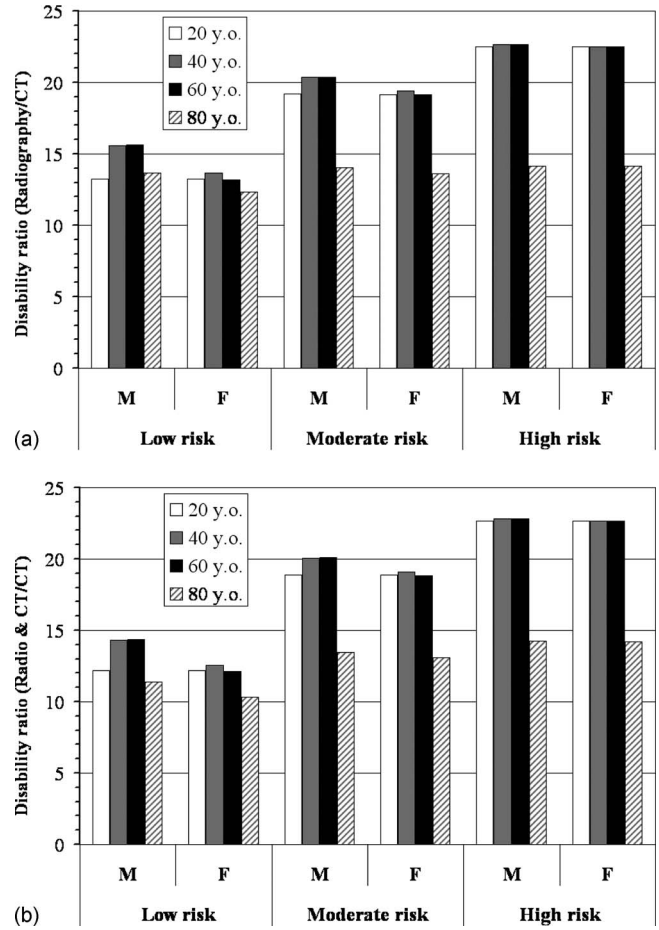

FIG. 5. Total disability ratios: (a) Radiography over CT and (b) radiography and CT over CT. Disability ratios larger than unity signify the superiority of CT over radiography or radiography and CT. Three different groups of risk patients (low, moderate, and high) at four ages (20, 40, 60, and 80 yr old) are considered for male (m) and female (f) patients.

chi-square: 0.10, and $p=0.748$). The latter values were used for the decision model calculations regarding the diagnostic accuracy of radiography.

III.C. Dosimetric results

According to the ESD measurements obtained by the simulated exposures, the patient effective dose from the three-view radiographic evaluation of the CS amounts to 0.050 mSv (0.034 mSv from the AP projection, 0.006 mSv from the LAT, and 0.010 mSv from the odontoid).

The mean DLP value of the helical CS scans was 512 cGy cm for the 50 male and 455 cGy cm for the 36 female patients included in our study. Our calculated sex-specific DLP to effective dose conversion coefficients were 0.007 57 and 0.007 47 mSv/cGy cm for females and males, respectively. As a result, the radiation burdens from a typical helical scan of the CS were estimated to be 3.8 and 3.4 mSv for the male and female patients, respectively.

III.D. Decision analysis model

The decision analysis model is illustrated in Fig. 4. Three imaging options are compared: CT, radiography, and radiography followed by CT when positive. The relationship between true positive, true negative, false positive, and false negative diagnosis and the sensitivity/specificity of the imaging modalities is also shown. Treatment strategy, postoperative mortality, and treatment outcomes (remission or paralysis) are stochastic variables with values presented in Table II.

III.E. Effectiveness of the imaging strategies

Figure 5 compares the effectiveness of the two modalities. The total disability from radiography [Fig. 5(a)] or radiography and CT [Fig. 5(b)] is divided by the corresponding expected disability when CT is used as the imaging modality of choice. Disability ratios larger than unity signify the superiority of CT usage alone over conventional radiography or radiography followed by CT. Three different groups of patient risk, low, moderate, and high, at four ages, 20, 40, 60 and 80 yr old, are considered for both sexes. Disability ratios radiography over CT vary with patient risk from 13.3, for low risk 20 yr old patients, to 22.6, for high risk 40 yr old patients. Disability ratios, radiography and CT over CT, vary with patient risk from 12.2, for low risk 20 yr old patients, to 22.8, for high risk 40 yr old patients. As the ratio increases, the use of CT becomes more favorable over the use of radiography, which is the case in the high risk patient group. The ratios for the 80 yr old patients are lower compared to other

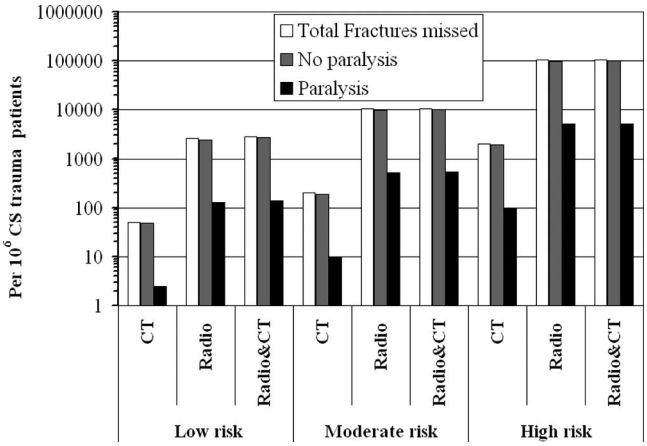

FIG. 6. Number of fractures missed per million examinees for each imaging strategy, leading or not to paralysis.

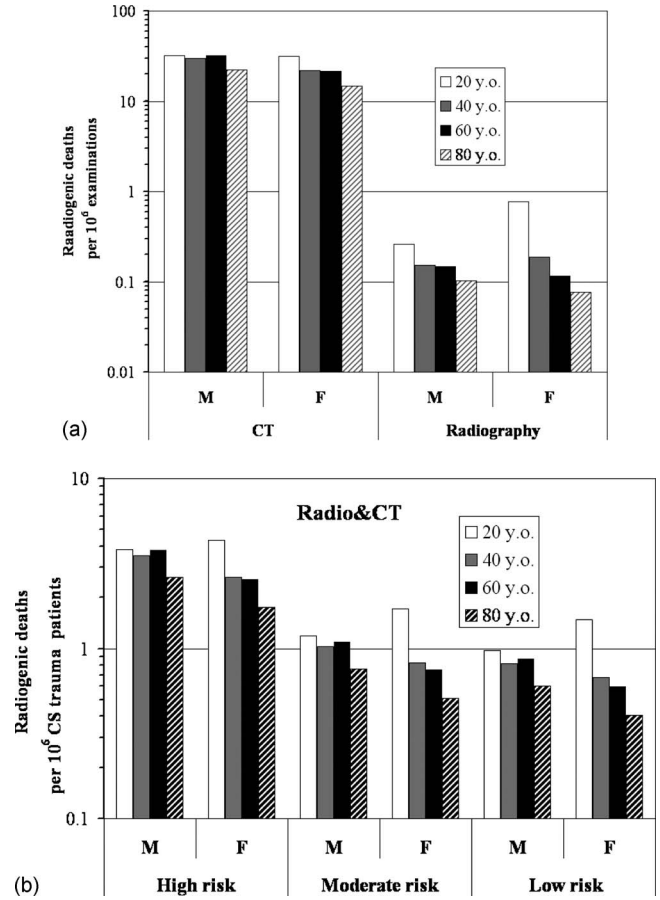

FIG. 7. Radiation effects (lethal cancer incidents per million examinees) of (a) CT alone and radiography alone for both sexes and four age groups, and (b) for radiography followed by CT, for both sexes, four age groups, and three fracture risk levels.

age groups since this patient cohort, although less radiosensitive, presents higher postoperative mortality (Table II). It is interesting to notice that the radiography and CT imaging strategy slightly outperforms the radiography alone option and only for high and moderate risk patients.

In Fig. 6 we compare the number of fractures missed, leading or not to paralysis, per million examinations. The number of missed fractures increases with the *a priori* fracture probability (patient risk). Radiography and radiography and CT yield approximately 50 times more false negative diagnoses than CT alone.

Radiation effects (total mortal cancers per million examinations) for both sexes are shown in Fig. 7. The use of CT in a hypothetical cohort of 10^6 patients prevents approximately 130 incidents of paralysis in the low risk group, 500 in the moderate risk group, and 5100 in patients with high *a priori* fracture probability. The expense of this CT-based prevention is, depending on age, sex, and risk, 15–32 radiogenic lethal cancer incidents additional to those potentially incurred by plain radiography or radiography followed by CT for positive findings.

IV. DISCUSSION

The dramatic increase in the CT usage over the past decade and the more accurately quantified radiogenic risk estimates have recently restimulated concerns about the clinical grounds on which CT examinations are prescribed.[5,6] Referring physicians should be able to assess the benefit versus potential detriment to the examinee and request the most beneficial among the available modalities. Hence, justification is an essential part of developing the imaging strategy since patients should not be deprived of the potential benefit arising from a CT scan.

Regarding the imaging evaluation of CS trauma patients, CT and radiography have been so far compared in two published studies but only in terms of financial costs, thus neglecting the radiation effects.[9,40] It was deduced that CT should be the preferred screening modality for high and moderate risk patients. To the best of our knowledge, no studies exist that compare CT to radiography followed by CT or that account for radiogenic detriment.

In the present study, a meta-analysis and systematic review of the published literature confirmed the superiority of performance of MDCT vs plain radiography for the clearance of patients suspected with cervical spine injury. Moreover, the calculations based on a decision analysis model established that, despite the increased radiation burden to the examinee, CT is associated with more favorable ratios of benefit to risk compared to radiography or radiography and CT, irrespective of risk group stratification (determined by the mechanism of trauma and the patient age) and patient radiosensitivity (depending on age at irradiation). It should be stressed that, as shown in Fig. 5, CT outweighs both radiography and radiography and CT even for the low risk highly radiosensitive patients (females of 20 yr old). The strength of this finding was investigated by recalculating the disability ratios for this patient subgroup for varying values of the probability of paralysis and of the sensitivity of radiography (sensitivity analysis). As shown in Fig. 8, the appropriateness of CT even for the most radiosensitive patient cohort is not affected by the two abovementioned variables. Even at a high hypothetical value of radiography specificity

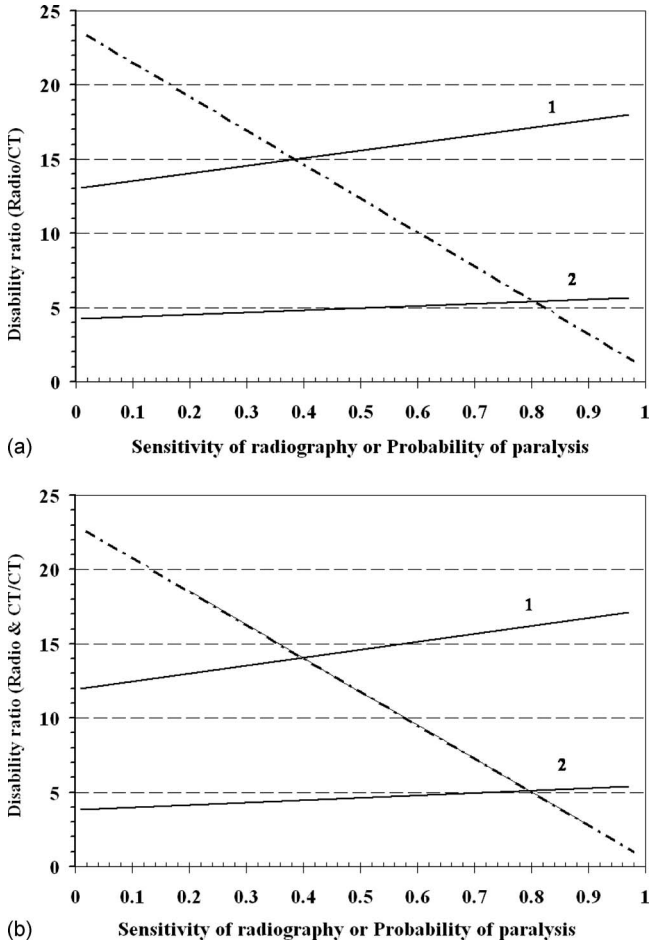

FIG. 8. (a) Variation in radiography over CT disability ratios (sensitivity analysis) with sensitivity of radiography (dashed line) for a 0.99 specificity value and with probability of paralysis due to a missed CS fracture for 0.99 radiography specificity and sensitivity of 0.483 (solid line 1) and of 0.85 (solid line 2). (b) Variation in radiography and CT over CT disability ratios (sensitivity analysis) with sensitivity of radiography (dashed line) for a 0.99 specificity value and with probability of paralysis due to a missed CS fracture for 0.99 radiography specificity and sensitivity of 0.483 (solid line 1) and of 0.85 (solid line 2).

(99%), the corresponding sensitivity needed for radiography to be equivalent CT is 0.997 and for radiography/CT to be equivalent to CT alone is 0.979. Hence, high values of sensitivity are needed for equivalent disability scores, which are not found in literature. Similarly, even at 0.99 specificity and a sensitivity value of 0.85 for radiography, the disability ratio is 4.26 for radiography over CT and 3.86 for radiography and CT over CT, for a probability of paralysis from a missed fracture as low as 0.01 (1%) (Fig. 8).

Sensitivity analysis was also performed with respect to the disability weights of paralysis and fracture. Figure 9 shows that even for an increased hypothetical diagnostic accuracy of radiography (sensitivity of 0.85 and specificity of 0.99), plain radiography or radiography followed by CT is equivalent to CT at a negative disability weight for paralysis, which is unrealistic. Figure 10 shows that even with the abovementioned increased diagnostic accuracy of radiography (sensitivity of 0.85 and specificity 0.99), and with a reduced disability weight of paralysis (0.1), plain radiography or radiography followed by CT is equivalent to CT only if the facture disability weight is in the range of 0.02–0.04, which is also unrealistic.

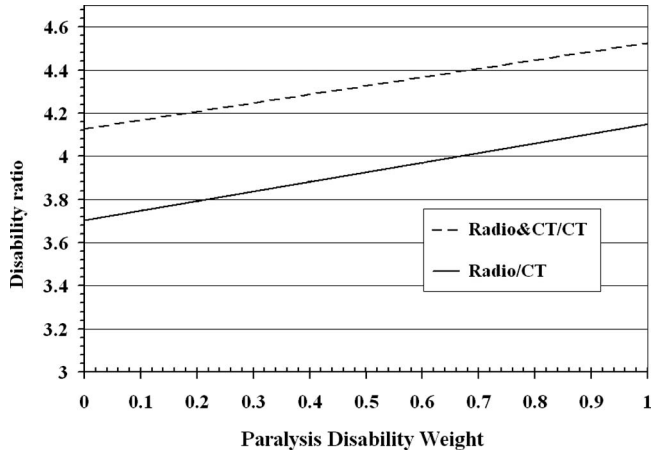

FIG. 9. Variation in disability ratios (sensitivity analysis) with paralysis disability weight for an increased hypothetical diagnostic accuracy of radiography (sensitivity of 0.85 and specificity of 0.99).

The unexpected finding of the very limited superiority of radiography and CT over plain radiography can be explained using Figs. 6 and 7. Implementation of the combined imaging protocol calls for 112 600, 29 260 and 22 315 CT scans per million patients of high, medium, and low risk patients, respectively, incurring one to four extraneous radiogenic deaths. Since only patients with positive radiographs are CT scanned, no false negative findings will be revealed. On the contrary, because of the 0.99 CT sensitivity, a fraction of the true positive radiograph-based diagnoses will be canceled following false negative CT scans, leading to 1126, 293, and 223 fractures missed per million high, medium, and low risk patients, respectively, additional to plain radiography, or 56, 14, and 11 cases of paralysis. The actual benefit of CT usage

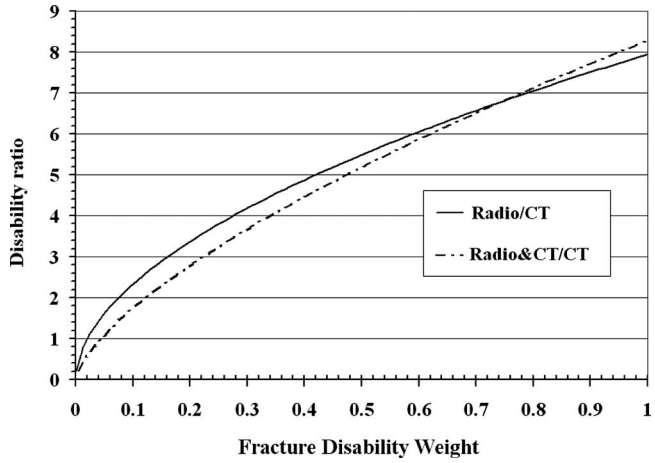

FIG. 10. Variation in disability ratios (sensitivity analysis) with fracture disability weight for an increased hypothetical diagnostic accuracy of radiography (sensitivity of 0.85 and specificity of 0.99) and a disability weight for paralysis reduced to 0.1.

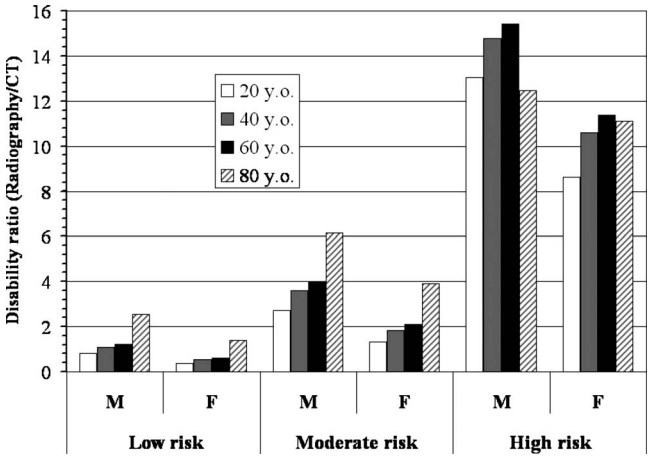

FIG. 11. Disability ratios (radiography over CT) derived from radiogenic risks based on organ-absorbed doses associated with CT coronary angiography. Ratios are provided for three different risk groups (low, moderate, and high), four ages at irradiation (20, 40, 60, and 80 yr old), and separately for male (m) and female (f) patients.

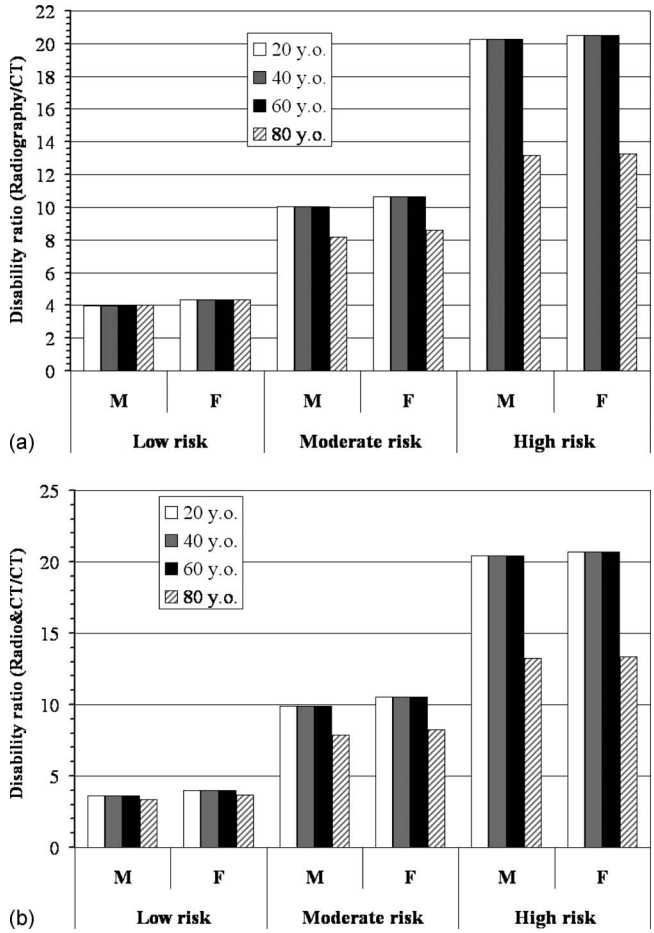

FIG. 12. Disability ratios: (a) Radiography/CT and b) radiography and CT/CT, derived from radiogenic risks based on the effective dose concept. Ratios are provided for male (m) and female (f) patients, three different risk groups (low, moderate, and high), and four ages at irradiation (20, 40, 60, and 80 yr old).

following positive radiography is the prevention of postoperative death of examinees without deficit, who would undergo surgery due to false positive radiography, i.e., 64, 78, and 80 deaths per million high, medium, and low risk patients, respectively.

In the present study, radiation risk assessment was based on an up-to-date report derived from credible epidemiological data.[11] Organ-specific coefficients per age group and sex were combined with the Monte Carlo derived organ-absorbed doses. Radiogenic risk from CT or radiography originates primarily from the irradiation of the thyroid and red bone marrow (RBM). Male patients are 1.3 times more susceptible to leukemia compared to female patients and the radiosensitivity of RBM drops by 30% from age 20 to age 80 yr. The incidence of thyroid cancer is 4.4 higher on female patients in the 20–60 yr old age group and drop to 0 for both sexes over the age of 80. However, the mortality associated with thyroid cancer is as low as 7%.[41] Hence, although the radiation burden to the thyroid is four times higher than that to the RBM, the fatal leukemia risk is 2, for the young examinees, to 200 times higher than the mortality risk of thyroid cancer. Because of the dose distribution of the specific examination, the radiogenic risk is low enough to render CT utilization justified even for the low risk patient cohort.

The importance of accurate dose and risk assessment for the purpose of justification can be highlighted by recalculating the disability ratios for a CT examination of higher burden such as coronary angiography. Figure 11 illustrates that if the dose to the stomach, lung, and thyroid was equal to that from a coronary angiography scan,[12] then the utilization of CT would not be justified for the low risk patient cohort. Similarly, the importance of applying the organ-specific methodology for the risk assessment may be shown by recalculating the risk and the corresponding disability ratios using the effective dose to the patient from CT and radiography and the risk coefficient for adults proposed by ICRP in 1990 (5×10^{-2} Sv^{-1}).[42] Had we used the effective dose based risk assessment method would have overestimated radiogenic mortality by factors of 5–12 for CT and by factors of 3–32 for radiography. As a result, the disability ratios would have been 1.5–4 times lower for the low and moderate risk patient groups (Fig. 12). It is therefore evident that the process of justification regarding the use of CT in the clearance of CS trauma patients had to be performed in the light of the new information about the dosimetric characteristics and diagnostic performance of the modern MDCT scanners and the radiosensitivity of the examinees.

V. CONCLUSIONS

In conclusion, the application of a decision model incorporating up-to-date organ-specific radiation risk assessment has shown that for the evaluation of CS trauma, the higher diagnostic accuracy obtained by the CT examination counterbalances the increase in dose compared to plain radiography or radiography followed by CT for positive findings and renders CT utilization dose effective and justified regardless of the patient age, sex, and fracture risk.

ACKNOWLEDGMENT

This work was supported by the European Community, a specific targeted research project, under the FP6 Specific programme for research and training on nuclear energy (Safety and Efficacy of CT, Contract No. FP6/002388).

APPENDIX: LITERATURE SEARCH

We searched the most popular literature databases (MEDLINE, EMBASE, Web of Science, and Cochrane Database of Systematic Reviews) for diagnostic cohort studies of patients with low or intermediate severity cervical spine trauma who were imaged by means of CT and were published between 2000 and 2008, or radiography and were published between 1996 and 2008. Our search strategy in MEDLINE was as follows: Search terms: (cervical spine OR cervical OR neck) AND (trauma) AND ("diagnostic accuracy" OR sensitivity) AND (specificity OR "true positive" OR "true negative" OR "false positive" OR "false negative" OR "true positives" OR "true negatives" OR "false positives" OR "false negatives" OR "predictive value" OR "predictive values" OR "likelihood ratio" OR "positive likelihood" OR "negative likelihood" OR "receiver operating characteristics" OR "ROC" OR "reference value" OR "reference values" OR "normal value" OR "normal values" OR "confidence interval" OR "confidence intervals") AND ("MDCT" OR tomography) AND has abstract[text] AND English[lang] AND "humans"[MeSH Terms] AND ("2000"[PDAT]: "3000"[PDAT]) and limits: only items with abstracts, English, humans, adults (>19 yr old). For the other databases, search strategy was adapted to the needs of the specific search engine. Automated retrieval was complemented with a manual search through the literature of review articles, for potentially relevant articles that were not identified by the original search.

We included in our study (a) original prospective or retrospective studies assessing the role of CT or radiography in the evaluation of the CS injury, (b) articles including two x-ray views of the spine at the minimum, and (c) articles adequately reporting performance values (true positive, true negative, false positive, and false negative). Case reports, review articles, pictorial essays, unpublished data, abstracts, and letters to the editor were excluded from the study. Furthermore, publications focusing on topics other than diagnostic test assessment and effectiveness analyses, such as management decision issues and technical exhibitions or studies employing dynamic radiographic views (flexion, extension, etc) not fulfilling the above mentioned criteria, were also excluded.

[a]Author to whom correspondence should be addressed. Electronic mail: damilaki@med.uoc.gr; Telephone: +30-2810-392569; Fax: +30-2810-542095.

[1]Royal College of Radiologists, *Making the Best Use of a Department of Clinical Radiology*, 5th ed. (Royal College of Radiologists, London, 2003).

[2]J. R. Hoffman, W. R. Mower, A. B. Wolfson, K. H. Todd, and M. I. Zucker, "Validity of a set of clinical criteria to rule out injury to the cervical spine in patients with blunt trauma. National Emergency X-Radiography Utilization Study Group," N. Engl. J. Med. **343**, 94–99 (2000).

[3]I. G. Stiell, G. A. Wells, K. L. Vandemheen, C. M. Clement, H. Lesiuk, V. J. De Maio, A. Laupacis, M. Schull, R. D. McKnight, R. Verbeek, R. Brison, D. Cass, J. Dreyer, M. A. Eisenhauer, G. H. Greenberg, I. MacPhail, L. Morrison, M. Reardon, and J. Worthington, "The Canadian C-spine rule for radiography in alert and stable trauma patients," JAMA, J. Am. Med. Assoc. **286**, 1841–1848 (2001).

[4]P. T. McCulloch, J. France, D. L. Jones, W. Krantz, T. P. Nguyen, C. Chambers, J. Dorchak, and P. Mucha, "Helical computed tomography alone compared with plain radiographs with adjunct computed tomography to evaluate the cervical spine after high-energy trauma," J. Bone Jt. Surg., Am. Vol. **87**, 2388–2394 (2005).

[5]D. J. Brenner and E. J. Hall, "Computed tomography:an increasing source of radiation exposure," N. Engl. J. Med. **357**, 2277–2284 (2007).

[6]E. J. Hall and D. J. Brenner, "Cancer risks from diagnostic radiology," Br. J. Radiol. **81**, 362–378 (2008).

[7]J. Bernstein, "Decision analysis," J. Bone Jt. Surg., Am. Vol. **79**, 1404–1414 (1997).

[8]M. S. Kocher and D. Zurakowski, "Clinical epidemiology and biostatistics: A primer for orthopaedic surgeons," J. Bone Jt. Surg., Am. Vol. **86**, 607–620 (2004).

[9]C. C. Blackmore, S. D. Ramsey, F. A. Mann, and R. A. Deyo, "Cervical spine screening with CT in trauma patients: A cost-effectiveness analysis," Radiology **212**, 117–125 (1999).

[10]J. Zamora, V. Abraira, A. Muriel, K. S. Khan, and A. Coomarasamy, "Meta-DiSc: A software for meta-analysis of test accuracy data," BMC Med. Res. Methodol. **6**, 31–43 (2001).

[11]Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation; Nuclear and Radiation Studies Board, Division on Earth and Life Studies, National Research Council of the National Academies, *Health Risks From Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (The National Academies, Washington, DC, 2006).

[12]A. J. Einstein, M. J. Henzlova, and S. Rajagopalan, "Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography," JAMA, J. Am. Med. Assoc. **298**, 317–323 (2007).

[13]K. Faulkner, D. A. Broadhead, and R. M. Harrison, "Patient dosimetry measurement methods," Appl. Radiat. Isot. **50**, 113–123 (1999).

[14]Imaging Performance Assessment of CT (ImPACT), St. George's Hospital, London, UK, CT Patient Dosimetry Calculator (Version 0.99w, June 2005, available at http://www.impactscan.org).

[15]O. Johnell, B. Jönsson, L. Jönsson, and D. Black, "Cost effectiveness of alendronate (fosamax) for the treatment of osteoporosis and prevention of fractures," Pharmacoeconomics **21**, 305–314 (2003).

[16]C. C. Blackmore, S. S. Emerson, F. A. Mann, and T. D. Koepsell, "Cervical spine imaging in patients with trauma: Determination of fracture risk to optimize use," Radiology **211**, 759–765 (1999).

[17]Z. N. Irwin, M. Arthur, R. J. Mullins, and R. A. Hart, "Variations in injury patterns, treatment, and outcome for spinal fracture and paralysis in adult versus geriatric patients," Spine **29**, 796–802 (2004).

[18]A. P. Jackson, M. H. Haak, N. Khan, and P. R. Meyer, "Cervical spine injuries in the elderly: Acute postoperative mortality," Spine **30**, 1524–1527 (2005).

[19]D. C. Reid, R. Henderson, L. Saboe, and J. D. Miller, "Etiology and clinical course of missed spine fractures," J. Trauma **27**, 980–986 (1987).

[20]J. W. Davis, D. L. Phreaner, D. B. Hoyt, and R. C. Mackersie, "The etiology of missed cervical spine injuries," J. Trauma **34**, 342–346 (1993).

[21]H. C. Sox, M. A. Blatt, M. C. Higgins, and K. I. Marton, *Medical Decision Making* (Butterworth, Boston, MA, 1988).

[22]B. Efron and R. J. Tibshirani, *An Introduction to the Bootstrap* (Chapman and Hall, New York, NY, 1993).

[23]B. D. Gerrelts, E. U. Petersen, J. Mabry, and S. R. Petersen, "Delayed diagnosis of cervical spine injuries," J. Trauma **31**, 1622–1626 (1991).

[24]A. E. Ajani, D. J. Cooper, C. D. Scheinkestel, J. Laidlaw, and D. V. Tuxen, "Optimal assessment of cervical spine trauma in critically ill patients: A prospective evaluation," Anaesth. Intensive Care **26**, 487–491 (1998).

[25]P. J. Schenarts, J. Diaz, C. Kaiser, Y. Carrillo, V. Eddy, and J. A. Morris, "Prospective comparison of admission computed tomographic scan and plain films of the upper cervical spine in trauma patients with altered mental status," J. Trauma **51**, 663–668 (2001).

[26]C. M. Bach, I. E. Steingruber, S. Peer, R. Peer-Kühberger, W. Jaschke, and M. Ogon, "Radiographic evaluation of cervical spine trauma. Plain radiography and conventional tomography versus computed tomogra-

phy," Arch. Orthop. Trauma Surg. **121**, 385–387 (2001).
[27]M. M. Griffen, E. R. Frykberg, A. J. Kerwin, M. A. Schinco, J. J. Tepas, K. Rowe, and J. Abboud, "Radiographic clearance of blunt cervical spine injury: Plain radiograph or computed tomography scan?" J. Trauma **55**, 222–226 (2003).
[28]J. J. Diaz, C. Gillman, J. A. Morris, A. K. May, Y. M. Carrillo, and J. Guy, "Are five-view plain films of the cervical spine unreliable? A prospective evaluation in blunt trauma patients with altered mental status," Trauma **55**, 658–663 (2003).
[29]S. Widder, C. Doig, P. Burrowes, G. Larsen, R. J. Hurlbert, and J. B. Kortbeek, "Prospective evaluation of computed tomographic scanning for the spinal clearance of obtunded trauma patients: Preliminary results," J. Trauma **56**, 1179–1184 (2004).
[30]J. J. Diaz, J. M. Aulino, B. Collier, C. Roman, A. K. May, R. S. Miller, O. Guillamondegui, and J. A. Morris, "The early work-up for isolated ligamentous injury of the cervical spine: Does computed tomography scan have a role?," J. Trauma **59**, 897–903 (2005).
[31]G. K. Nguyen and R. Clark, "Adequacy of plain radiography in the diagnosis of cervical spine injuries," Emerg. Radiol. **11**, 158–161 (2005).
[32]C. A. Barba, J. Taggert, A. S. Morgan, J. Guerra, B. Bernstein, M. Lorenzo, A. Gershon, and N. Epstein, "A new cervical spine clearance protocol using computed tomography," J. Trauma **51**, 652–656 (2001).
[33]K. Brohi, M. Healy, T. Fotheringham, O. Chan, C. Aylwin, S. Whitley, and M. Walsh, "Helical computed tomographic scanning for the evaluation of the cervical spine in the unconscious, intubated trauma patient," J. Trauma **58**, 897–901 (2005).
[34]C. V. Brown, J. L. Antevil, M. J. Sise, and D. I. Sack, "Spiral computed tomography for the diagnosis of cervical, thoracic, and lumbar spine fractures: Its time has come," J. Trauma **58**, 890–895 (2005).
[35]B. Sanchez, K. Waxman, T. Jones, S. Conner, R. Chung, and S. Becerra, "Cervical spine clearance in blunt trauma: Evaluation of a computed tomography-based protocol," J. Trauma **59**, 179–183 (2005).
[36]S. C. Gale, V. H. Gracias, P. M. Reilly, and C. W. Schwab, "The inefficiency of plain radiography to evaluate the cervical spine after blunt trauma," J. Trauma **59**, 1121–1125 (2005).
[37]R. Mathen, K. Inaba, F. Munera, P. G. Teixeira, L. Rivas, M. McKenney, P. Lopez, and C. J. Ledezma, "Prospective evaluation of multislice computed tomography versus plain radiographic cervical spine clearance in trauma patients," J. Trauma **62**, 1427–1431 (2007).
[38]J. D. Berne, G. C. Velmahos, Q. El-Tawil, D. Demetriades, J. A. Asensio, J. A. Murray, E. E. Cornwell, H. Belzberg, and T. V. Berne, "Value of complete cervical helical computed tomographic scanning in identifying cervical spine injury in the unevaluable blunt trauma patient with multiple injuries: A prospective study," J. Trauma **47**, 896–902 (1999).
[39]D. B. Nunez, A. Zuluaga, D. A. Fuentes-Bernardo, L. A. Rivas, and J. L. Becerra, "Cervical spine trauma: How much more do we learn by routinely using helical CT?," Radiographics **16**, 1307–1318 (1996).
[40]E. L. Grogan, J. A. Morris, Jr., R. S. Dittus, D. E. Moore, B. K. Poulose, J. J. Diaz, and T. Speroff, "Cervical spine evaluation in urban trauma centers: Lowering institutional costs and complications through helical CT scan," J. Am. Coll. Surg. **200**, 160–165 (2005).
[41]International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection, Publication No. 103 (The International Commission on Radiological Protection, 2007).
[42]International Commission on Radiological Protection, 1990 Recommendations of the International Commission on Radiological Protection, Publication No. 60 (The International Commission on Radiological Protection, New York, 1991).