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FULL PAPER

Whole-body CT-based imaging algorithm for multiple trauma patients: radiation dose and time to diagnosis

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Objective: To determine the number of imaging examinations, radiation dose and the time to complete trauma-related imaging in multiple trauma patients before and after introduction of whole-body CT (WBCT) into early trauma care.

Methods: 120 consecutive patients before and 120 patients after introduction of WBCT into the trauma algorithm of the University Hospital Zurich were compared regarding the number and type of CT, radiography, focused assessment with sonography for trauma (FAST), additional CT examinations (defined as CT of the same body regions after radiography and/or FAST) and the time to complete trauma-related imaging.

Results: In the WBCT cohort, significantly more patients underwent CT of the head, neck, chest and abdomen ($p < 0.001$) than in the non-WBCT cohort, whereas the number of radiographic examinations of the cervical spine, chest and pelvis and of FAST examinations were

significantly lower ($p < 0.001$). There were no significant differences between cohorts regarding the number of radiographic examinations of the upper ($p = 0.56$) and lower extremities ($p = 0.30$). We found significantly higher effective doses in the WBCT (29.5 mSv) than in the non-WBCT cohort (15.9 mSv; $p < 0.001$), but fewer additional CT examinations for completing the work-up were needed in the WBCT cohort ($p < 0.001$). The time to complete trauma-related imaging was significantly shorter in the WBCT (12 min) than in the non-WBCT cohort (75 min; $p < 0.001$).

Conclusion: Including WBCT in the initial work-up of trauma patients results in higher radiation doses, but fewer additional CT examinations are needed, and the time for completing trauma-related imaging is shorter.

Advances in knowledge: WBCT in trauma patients is associated with a high radiation dose of 29.5 mSv.

CT represents an important imaging modality in the evaluation of trauma patients and traditionally was performed after an initial evaluation with conventional radiography and sonography. Owing to technical developments, whole-body CT (WBCT) became feasible, which led to its integration into the early work-up of patients.^{1–5} A recent retrospective multi-centre study suggested that the use of WBCT as the primary imaging modality would significantly increase the probability of survival in patients with multiple trauma compared with an imaging algorithm using radiography, sonography, eventually followed by CT of selected body regions.⁶ Thus, WBCT was recommended by various authors as the primary diagnostic method for trauma patients,^{7,8} even when such patients are borderline haemodynamically unstable.^{2,9–11}

However, the true benefit of WBCT remains a matter of debate. A recent systematic review demonstrated that it is

still not determined whether the benefit in terms of decreased mortality is a true effect of WBCT or is mediated through changes in the management of trauma patients.¹² Another relevant issue is the associated radiation dose of CT, in particular when employing WBCT.¹² Interestingly, most previous studies did not determine radiation doses of WBCT but rather provided estimates or extrapolations,^{6,13–15} and no study, to our knowledge, directly compared radiation doses of patients with multiple trauma undergoing radiography and selected CT with those undergoing WBCT, taking into account the additional CT imaging that was necessary for completing the trauma-related imaging work-up if radiography and sonography were not sufficient.

Thus, the purpose of our study was to assess the number of radiological investigations and radiation doses in the initial imaging evaluation of patients with multiple trauma before

and after the introduction of WBCT into early trauma care in our hospital. Furthermore, we determined the time from the patients' admission to the completion of trauma-related diagnostic work-up.

METHODS AND MATERIALS

Study population

Our study was conducted at a Level-I trauma centre after institutional review board approval was obtained. Written informed consent was waived by our local ethics committee because of the retrospective nature of the study.

From January to December 2008, a total of 120 consecutive trauma patients (89 males; mean age, 44.2 ± 18.6 years; range, 16–86 years) admitted to our resuscitation room were included as the non-WBCT cohort. These patients underwent trauma imaging with conventional radiography and sonography, and were eventually followed by CT.

In the same time interval in 2010, another 120 consecutive trauma patients (81 males; mean age, 46.7 ± 20.7 years; range, 17–91 years) who were also admitted to our resuscitation room were included as the WBCT cohort (Table 1). In both cohorts, only patients who were admitted directly from the incident scene and not transferred from other hospitals were included.

Definition of multiple trauma and indications for admission

A multiple trauma was defined as an injury of several body regions or organs, whereby at least one injury or the combination of several injuries was potentially life threatening.¹⁶ Patients were admitted to the resuscitation room according to previously published indications and conditions.

Settings

In the non-WBCT cohort, patients were assessed depending on their clinical condition according to the advanced trauma life support (ATLS®; American College of Surgeons, Chicago, IL) program including radiography, focused assessment with sonography for trauma (FAST) and CT. CT in this cohort was performed specifically and individually depending on the clinical situation and on the findings from radiography and FAST.

In July 2009, a new multiple trauma algorithm was introduced in our hospital, which included WBCT as the primary imaging modality (Figure 1). In brief, after report of the pre-hospital circumstances, medical assessment and clinically suspected injuries by the ambulance personnel, initial evaluation of patients with multiple trauma included an assessment of airways, breathing and circulation. Patients who were stable were directly transferred to the scanner for WBCT. Patients who were unstable were transferred to the resuscitation room for stabilization and radiography and FAST. After stabilization, these patients underwent WBCT. After interpretation of the results from WBCT, the trauma surgeon decided on damage control surgery or early total care.

Radiography

Radiography included an anteroposterior (AP) chest radiograph, a pelvic AP radiograph and a lateral radiograph of the cervical spine.¹⁷ Further radiographs were obtained according to individual clinical judgment and patient's requirements during secondary survey. All radiographs were performed in the resuscitation room on a mobile radiography system (Mobilett XP Hybrid; Siemens Healthcare, Forchheim, Germany).

Table 1. Patient demographics

Demographics and trauma mechanism	Non-WBCT cohort	WBCT cohort	<i>p</i> -value
Age (years) (mean $\pm$ standard deviation)	44.2 ± 18.6	46.66 ± 20.7	0.339
Sex (% male)	74.2%	67.5%	0.256
Injury severity score (median $\pm$ IQR)	22.0 ± 18.0	22.0 ± 20.0	0.838
New injury severity score (median $\pm$ IQR)	29.0 ± 21.0	27.0 ± 26.0	0.528
Blunt trauma	113	113	1.0
Penetrating trauma	7	7	1.0
Type of accident			0.424
Accident at work	18	12	
Motor vehicle accident	53	49	
Sports injury	13	11	
Accident at home	13	21	
Suicide	9	8	
Crime/offense	6	4	
Others	8	15	

IQR, interquartile range; WBCT, whole-body CT.

Figure 1. The current multiple trauma algorithm of our hospital. ABC, airway/breathing/circulation; CPR, cardiopulmonary resuscitation; FAST, focused assessment with sonography for trauma; WBCT, whole-body CT.

Sonography

Sonography was performed by the trauma surgeon in the resuscitation room according to FAST using a standard ultrasound system (iU22 xMATRIX; Philips Healthcare, Eindhoven, Netherlands).

CT

All examinations were performed using a 64-slice CT scanner (Somatom Sensation 64 and Somatom Definition; Siemens Healthcare) located immediately adjacent to the resuscitation room and included non-enhanced CT of the head, non-enhanced CT of the cervical spine and contrast-enhanced CT of the chest/abdomen.

The contrast media protocol was designed to provide a mixed arteriovenous phase of the chest and a portal-venous phase of the abdomen. 100 ml iso-osmolar, non-ionic iodinated contrast material [300 mg iodine per millilitre, iopromide (Ultravist®; Bayer Healthcare, Leverkusen, Germany)] followed by a saline flush of 30 ml was injected into an antecubital vein at a flow rate of 3 ml s⁻¹. All scans were performed using the following scan and reconstruction parameters: tube voltage, 120 kVp; slice thickness, 2 mm; increment, 1.6 mm, using filtered back projection. The reference tube current–time product was set at 200 mAs for the chest and at 250 mAs for the abdomen, using attenuation-based tube current modulation.

In the non-WBCT cohort, both arms were positioned outside of the scan field of view (FOV) in 72/120 (60%) patients, and one arm or both arms were positioned inside the scan FOV either next to the body ($n = 22$) or ventrally to the abdomen ($n = 26$) in 48 (40%) patients. Arm positioning within the scan FOV was performed in those patients not able to move their arms or who had contraindications for moving their arms. In the WBCT cohort, arms were positioned alongside the body in eight (7%) patients, and both arms on a pillow were located ventrally to the chest/upper abdomen with both arms flexed at the elbow in 112 (93%) patients.

All reconstructed images were archived in the picture archiving and communication system (IMPAX® 6.0; Agfa HealthCare, Mortsel, Belgium) of our hospital for further image analysis and documentary purposes.

Estimation of radiation dose

The effective dose (ED) of CT was calculated by multiplying the dose–length product (DLP) with organ-specific conversion factors. The DLP was taken from the individual patient protocol. Conversion factors were used from anthropomorphic adult phantoms (averaging male and female):¹⁸ 0.0021 mSv (mGy × cm)⁻¹ for head, 0.0059 mSv (mGy × cm)⁻¹ for neck, 0.014 mSv (mGy × cm)⁻¹ for chest, 0.015 mSv (mGy × cm)⁻¹ for abdomen and pelvis, and 0.015 mSv (mGy × cm)⁻¹ for trunk.

Since no individual radiation dose values were available for our conventional radiographic examinations, we used standard values of effective radiation doses:¹⁹ 0.054 mSv for chest, 0.675 mSv for pelvis, 0.107 mSv for cervical spine, 0.528 mSv for thoracic spine, 1.5 mSv for lumbar spine, 0.042 mSv for clavicle, 0.042 mSv for shoulder, 0.006 mSv for upper extremity, 0.0006 mSv for elbow, 0.0011 mSv for forearm, 0.0002 mSv for wrist and 0.0002 mSv for hand.

Definition of time to completion of trauma-related imaging

In the non-WBCT cohort, the time interval from the patients' arrival at the hospital to the last imaging examination, which completed the trauma-related diagnostic work-up, was determined. When CT was the modality completing the diagnostic work-up, the start of CT data acquisition was taken. Follow-up imaging examinations during the hospital stay were excluded. The indications for all imaging examinations in this cohort were reviewed by one reader and only those examinations were included for which the indication and clinical question were related to the trauma.

In the non-WBCT cohort, initial CT was defined as those CT examinations without prior imaging, and additional CT was defined as CT after previous imaging (e.g. CT of the cervical spine after radiography of the cervical spine, CT of the chest after undergoing chest radiography and CT of the abdomen after FAST).

Statistical analysis

Quantitative parameters were expressed as means ± standard deviations for normally distributed and medians ± interquartile ranges for non-normally distributed variables. Categorical variables were expressed as frequencies or percentages. Normality was tested using the Kolmogorov–Smirnov test. The unpaired Student's *t*-test for independent samples was used to test for differences between groups regarding age. Mann–Whitney *U* test was used to test for differences regarding injury severity score (ISS) and new ISS (NISS). The χ^2 test was used to test for differences between groups regarding gender and trauma mechanism. The Mann–Whitney *U* test was used for testing for differences regarding ISS, NISS and frequencies of radiographs, sonography, CT, estimated doses and time to complete imaging between groups. The Levene's test was used to test for differences

Table 2. Frequencies of CT examinations among cohorts

CT examinations	Non-WBCT cohort	WBCT cohort	<i>p</i> -value
Primary WBCT (%)	0	100	<0.001
WBCT after radiography and sonography (%)	55	0	<0.001
Head (%)	28.3	0	<0.001
Neck (%)	14.2	0	<0.001
Chest (%)	20	0	<0.001
Abdomen (%)	18.3	0	<0.001
Upper extremities (%)	0	5	0.013
Lower extremities (%)	5	3.4	0.520

WBCT, whole-body CT.

regarding variability of the time needed for accomplishing the primary trauma-related diagnostic work-up. Statistical analyses were conducted using commercially available software (SPSS®, release v. 21.0; SPSS Inc., Chicago, IL). A *p*-value <0.05 was considered statistically significant.

RESULTS

Patients

There were no significant differences between the non-WBCT and the WBCT cohort regarding age, gender, ISS, NISS, trauma mechanism and the type of accident (all *p* > 0.05, [Table 1](#)).

Frequency of imaging examinations

In the non-WBCT cohort, 100/120 (83.3%) patients received an initial CT, and 90 (75.0%) patients underwent an additional CT. 24 (26.7%) of these 90 patients received a CT of selected body regions in addition to radiography and FAST, and 66 (73.3%) patients underwent WBCT after radiography and FAST ([Table 2](#)). Four (3.3%) patients did not undergo CT after radiography and FAST.

In the WBCT cohort, 104/120 (86.7%) patients directly underwent primary WBCT, whereas 16 (13.3%) patients underwent radiography and FAST before WBCT because of compromised airways, tension pneumothorax, cardiac tamponade and haemodynamic instability ([Figure 1](#)). Potentially life-saving interventions in these patients prior to WBCT included securing the airways (*n* = 13), decompression of tension pneumothorax (*n* = 3), pericardiocentesis (*n* = 2) and haemorrhage control (*n* = 7) for stabilizing vital functions.

In the WBCT cohort, patients underwent CT imaging of the head, neck, chest and abdomen significantly more often than in the non-WBCT cohort (*p* < 0.001). There were also significantly more numbers of CT examinations of the upper (*p* = 0.013) but not of the lower extremities (*p* = 0.520) in the WBCT cohort ([Table 2](#)).

In the non-WBCT cohort, significantly more radiographic examinations of the cervical spine, chest and pelvis were performed (*p* < 0.001), whereas there were no significant differences for the upper and lower extremities ([Table 3](#)).

FAST was performed in 109/120 (90.9%) patients of the non-WBCT and in 7/120 (5.8%) patients (*p* < 0.001) of the WBCT cohort. These 7 patients were part of the 16 patients mentioned above who were unstable for immediate transfer to WBCT.

Radiation doses

The cumulative total effective radiation dose in all 120 patients (3538.3 vs 1903.6 mSv) as well as the ED per patient (29.5 vs 15.9 mSv) were significantly (*p* < 0.001) higher in the WBCT than in the non-WBCT cohort ([Figure 2](#)).

In the non-WBCT cohort, patients underwent additional CT imaging with a cumulative dose of 1561.6 mSv for all patients and of 13.0 mSv per patient (*p* < 0.001, [Table 4](#)).

The cumulative total EDs of cervical spine, chest and pelvic radiography were significantly higher in the non-WBCT than in the WBCT cohort (*p* < 0.001). By contrast, there were no

Table 3. Frequencies of radiography examinations among cohorts

Radiography examinations	Non-WBCT cohort	WBCT cohort	<i>p</i> -value
Cervical spine (%)	15	0	<0.001
Chest AP (%)	88.3	13.3	<0.001
Pelvis AP (%)	71.7	5.8	<0.001
Upper extremities (%)	33.3	34.2	0.556
Lower extremities (%)	36.7	36.7	0.300

AP, anteroposterior; WBCT, whole-body CT.

Figure 2. Estimated effective radiation doses per patient among cohorts. WBCT, whole-body CT.

significant (all, $p > 0.05$) differences among the cohorts regarding the EDs of radiography of the thoracic and lumbar spine and of the upper and lower extremities (Supplementary Table A).

Time to complete trauma-related diagnostic work-up

The median time to complete trauma-related imaging was significantly shorter in the WBCT cohort (mean, 12 ± 9 min; median, 8 ± 8 min) than in the non-WBCT cohort (mean, 75 ± 232 min; median, 19 ± 23 min; $p < 0.001$) (Figure 3). Also, the variability of the time needed for accomplishing the complete trauma-related diagnostic work-up was significantly longer in the non-WBCT than in the WBCT cohort ($p < 0.001$).

In the WBCT cohort, data acquisition of WBCT started within the first hour of admission in all 120 (100%) patients. In the non-WBCT cohort, the time to complete trauma-related imaging in 18/120 (15%) patients was longer than 1 h; in 14/18 (78%) patients; the imaging was completed between 1 and 6 h; in 3 (17%) patients between 6 and 24 h; and in 1 (5%) patient after 24 h (Figure 4).

DISCUSSION

Radiation doses of imaging protocols must be accurately determined before the presumed long-term risk for cancer development from ionizing radiation can be estimated.^{20,21} This

holds true particularly in young multiple trauma patients and who often receive repeated CT examinations.²² Most previous studies in trauma patients, however, did not determine radiation doses.¹²

Huber-Wagner et al⁶ reported effective radiation doses of 10–20 mSv for WBCT, but individual radiation doses were not determined in their study and were estimated using the review article from Brenner and Elliston.²³ In another study by Huber-Wagner et al,⁹ radiation doses were stated to range between 5 and 10 mSv. Sierink et al¹³ reported effective radiation doses of 24 mSv for WBCT by estimating doses from a catalogue published by Mettler et al¹⁴ and by calculating representative radiation doses based on optimized trauma CT protocols at their trauma centre. Asha et al¹⁵ reported effective radiation doses of 23.9 mSv for WBCT by extrapolating the average doses of ten patients in their study.

We found only two studies assessing radiation doses of WBCT. Winslow et al²⁴ measured a median ED of 34 mSv for WBCT by multiplying individual DLPs of 79 patients using region-specific conversion factors. Ptak et al²⁵ calculated an average DLP of 3217 mGy cm^{-1} for WBCT by summing the segmental DLP from the individual scan segments for each patient. Our results revealed an average effective radiation dose of 29.5 mSv in a cohort based on radiation dose information in each individual patient, and are in line with the two studies mentioned above,^{24,25} similarly demonstrating radiation dose values being higher than the estimations and extrapolations of other publications.^{6,9,15,26}

WBCT, including single-pass, continuous acquisitions, is associated with a lower radiation dose than that associated with a segmented, partially overlapping protocol.²⁵ Our WBCT protocol used a segmented approach with overlap in the upper abdomen. Brink et al²⁷ reported that the effective radiation dose of a thoracoabdominal CT was increased by 45% when positioning the arms next to the torso than when positioning the arms above the head, because of the use of automated attenuation-based tube current modulation. Similar results were also shown by Loewenhardt et al.²⁸ In our non-WBCT cohort, 60% of patients were able to raise their arms above their heads (thus being outside the scan FOV), whereas our WBCT protocol was designed with arms on a pillow ventrally

Table 4. Estimated effective radiation doses from CT imaging

Estimated effective radiation doses	Non-WBCT cohort	WBCT cohort	<i>p</i> -value
Initial imaging, cumulative dose in 120 patients (mSv)	342.0	3538.3	<0.001
Additional CT imaging, cumulative dose in 120 patients (mSv)	1561.6	0	<0.001
Total cumulative dose in 120 patients (mSv)	1903.6	3538.3	<0.001
Initial imaging, per patient (mSv)	2.9	29.5	<0.001
Additional CT imaging, per patient (mSv)	13.0	0	<0.001
Total radiation dose, per patient (mSv)	15.9	29.5	<0.001

WBCT, whole-body CT.

Figure 3. Box plots showing the differences between times to complete trauma-related diagnostic work-up among cohorts. The horizontal lines in boxes correspond to the mean. The top and bottom of the boxes correspond to the second and third quartiles. The vertical lines extend to the mean ± 1.5 times the interquartile range. WBCT, whole-body CT.

to the chest/upper abdomen for reducing the time needed for changing arm positions between scans of different body parts.^{25,29–31}

In our non-WBCT cohort, 96.7% of patients underwent CT in addition to radiography and FAST. Of these, 39.8% received a CT of selected body regions and 56.9% received a WBCT. This high number of additional CT examinations in the non-WBCT cohort highlights the need for accurate imaging in the trauma patient that cannot be provided when using radiography and sonography alone.

The high use of CT was paralleled by an effective radiation dose of 16.5 mSv per patient in the non-WBCT cohort, equalling a 49% lower radiation dose than that of the WBCT cohort. These radiation dose values are comparable to those estimated by Sierink et al¹³ (16 mSv) and by Huber-Wagner et al⁶ (estimated 5–16 mSv for selective CT plus 2 mSv for a conventional radiography series). Still, because patients from the WBCT cohort received on average more CT examinations of the head, cervical spine, chest and abdomen, potential overutilization can be assumed when integrating WBCT as a standard imaging tool into early trauma care.

Time represents one of the most critical factors in early trauma care. In their WBCT cohort, Ptak et al³ measured an average time of 23 min for the time spent in the CT bay. Huber-Wagner et al⁶ reported an average time of 35.5 min for the WBCT cohort from trauma room admission to CT, as opposed to 46.6 min in the non-WBCT cohort. Wurmb et al³² reported a median time of 23 min for the WBCT cohort and 70 min for the non-WBCT cohort, measured from the patient's arrival to the end of diagnostic procedures including CT and first image interpretations by radiologists. Weninger et al³³ reported that the full extent of

injuries was definitely diagnosed by 12 min in 92.4% of their WBCT cohort, and definite diagnosis was possible in 76.2% patients of the non-WBCT cohort by 41 min.

Our study revealed an average time of 12 min in the WBCT cohort from hospital admission to the start of the WBCT scan. In the non-WBCT cohort, the average time between admission to the resuscitation room and the beginning of the last imaging examination completing imaging was 75 min. Interestingly, imaging in this cohort was completed in 15% of patients in more than 1 h and in 3% of patients as long as 6 h after hospital admission. Differences between our time intervals and those reported in the literature might be related to different diagnostic algorithms and patient pathways, as well as to variations in CT scanner locations.

There are some limitations to our study. First, the retrospective nature of our study has inherent shortcomings. Second, our study did not address patient outcomes but focused on frequencies of imaging examinations, associated radiation dose levels and time intervals for completing imaging. Third, at the time of this study, no iterative reconstructions were available on our CT scanner, and thus a valuable method for reducing radiation dose³⁴ could not be tested herein. On the other hand, our CT protocol is characterized by a single-phase acquisition that lowers the radiation dose in contrast to the higher radiation dose of recently advocated multiphase protocols in trauma patients.³⁵ Finally, our single-centre experience might not translate to other institutions with different algorithms, limiting the generalizability of results.

In conclusion, our study indicates that WBCT is associated with a radiation dose as high as 29.5 mSv per trauma patient, being considerably higher than what was previously stated but not measured in most studies.^{6,13–15} By contrast, the time for completing trauma-related imaging is shorter for WBCT than for an algorithm including radiography and sonography, eventually followed by selective use of CT.

Figure 4. Time to additional CT imaging examinations for obtaining complete trauma-related diagnostic work-up in the non-whole-body CT cohort.

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