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CT Protocol Optimization in Trauma Imaging: A Review of Current Evidence

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Abstract
Purpose of Review Trauma constitutes a social and a clinical problem. The CT protocol to be adopted in polytrauma patients is still not standardized across institutions. A variety of protocols can be found in the available literature, which differ from each other in timing acquisition and number of phases.
Recent Findings Even if multiple recent studies are investigating the role of split bolus technique, multiphasic protocol has been shown to be associated with early detection and adequate characterization of vascular injuries, so it should be still considered as the "best" CT protocol for the assessment of high-energy trauma patients.
Summary The article provides a review on the currently available literature on the CT protocols adopted in polytraumatized patients.

Keywords Polytrauma imaging · Whole-body CT · Polytrauma imaging protocol · Polytrauma imaging CT protocol · Vascular injuries · Active bleeding imaging · Parenchymal injuries

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Introduction

Trauma constitutes a social and a clinical problem: social, as it represents one of the most common causes of death or permanent disability in the population below 40 years [1••, 2••, 3, 4], and clinical, as patients may manifest a variety of presentations. Yet, there remains no consensus on the best diagnostic protocols to be utilized for trauma imaging amongst institutions [5••].

In the emergency setting, radiologists play a crucial role in the diagnosis and management of trauma patients, being members of the Trauma Team [6], with an adequate training in CT trauma studies [7, 8•]. Together with other trauma specialists, including emergency physicians, surgeons, anesthesiologists, and ancillary staff, radiologists have the responsibility to care for trauma patients providing important detailed information for timely management [8•].

The mechanism of trauma and not only the clinical presentation should guide the imaging work-up, distinguishing between two categories: minor trauma and major (poly-)trauma, and remembering that the probability of survival following the traumatic event, depend both on the mechanism of the trauma itself, but also on the timing and modalities of patient management, especially in the first hour following the event, commonly referred as the "golden hour" [2••].

In minor trauma, most hospitals in Europe adopt head CT (when needed), chest and skeletal radiographs, and ultrasonography (US) as the first-line imaging techniques. In the majority of Europe, US is performed by a consultant radiologist working 24/7 in the emergency department, for assessment of free fluid in the peritoneal, pericardial, and pleural spaces [8•], although, this may not be the case in other areas as Emergency Physicians or Trauma Surgeons tend to perform FAST/eFAST scans in the emergency department. Moreover, US may reach good sensitivity and specificity for the identification of intra-abdominal solid organ injuries, and in case of doubtful findings it can be integrated by intravenous contrast medium (contrast-enhanced US -CEUS-) if needed [8•, 9–11, 12•, 13]. However, US may be limited by patient habitus, lack of patient cooperation and reflex bowel distention (ileus) and not ensure a sufficient assessment of the retroperitoneum. This approach reduces the number of CT scans and the associated radiation dose exposure, but increases the total examination time and number of false negatives. While the risk of under diagnosis may be acceptable in minor trauma patients, considering the low incidence of significant conditions, this is not acceptable in major trauma patients, in whom the trauma mechanism exposes the patient to potentially unstable injuries, that need to be promptly ruled out.

Major trauma can be defined as a pathophysiological event consisting of: a sudden deceleration, impact or compression [14, 15] at speeds more than 65 km/h in car accidents, more than 45 km/h in motorcycle trauma [16], a fall from a height greater than 3 m, or a crush injury by heavy objects [17, 18].

In this category of patients, multi-detector CT (MDCT) should be considered the reference imaging standard, with a sensitivity of 95% and a negative predictive value approaching 100% to depict injuries [19–22]. Furthermore, CT allows the detection of otherwise undiagnosed injuries in 22% of cases [23], and additional findings that may change the management in up to 34% of patients [24, 25, 26•]. There is still not sufficient evidence to demonstrate a beneficial effect on survival by employing fast and detailed diagnostic work-up by immediate total-body CT, however, time to treatment is reported to be shorter for polytrauma patients who underwent diagnostic assessment with total-body CT scanning [26•, 27•].

Indeed, the current technical progress makes it possible to CT image the patient in a very short time, allowing to get a prompt and detailed diagnosis of parenchymal and vascular injuries, active bleeding as well as bone injuries, in few minutes. This contributed to the change of the "classic paradigm" of invasive laparotomy, to a non-operative management whenever possible, thus reducing mortality and morbidity [7, 8•, 28, 29]. Given its high negative predictive value, MDCT permits the early discharge of the patient, saving the costs of unnecessary hospitalization, when it is appropriate to do so [26•, 30].

CT Protocols

The CT protocol to be adopted in trauma patients is still not standardized across institutions. A variety of protocols can be found in the available literature, which differ from each other in timing acquisition and number of phases. This is related with the continuous attempts to find a good compromise between reduction of radiation exposure for usually young patients, and adequate imaging quality (Table 1). But, in an era in which we moved to non-operative management of polytraumatized patients, also other aspects, beyond the imaging quality need to be considered when choosing the best protocol. Indeed, the real capability to detect and to characterize in detail the injuries, particularly vascular injuries, guides the choice among the different therapeutic options. By adopting this approach, emergency radiologists can assume a leading role to ensure timely and accurate diagnosis of all trauma related injuries.

Monophasic CT Protocols

The monophasic protocol consists in a single MDCT acquisition after the intravenous (IV) administration of the contrast medium (CM), extended from the neck to the pelvis, and preceded by an unenhanced scan of the head. The protocols described in the literature vary by the rate of injection and the acquisition delay: 100 mL of contrast medium administered at an infusion rate of 4 mL/s with acquisition 60 s after the end of the injection [31] or 120 mL at 2 mL/s followed by 60 mL of physiological solution at the same infusion rate with acquisition at 85 s since the start of the injection [32] are the most commonly adopted, but others are also described with further differences in the infusion rate of the contrast media [33•, 34–36]. In the authors' opinion, MDCT studies performed with these protocols may be sub-optimal, not allowing an adequate identification and characterization of vascular injuries which may be present at the time of imaging and masked by the timing of the acquisition, such as pseudoaneurysms, arterial injuries and dissections. Indeed, these injuries are depicted during the dedicated arterial phase of acquisition [1••, 5••].

Multiphasic CT Protocol

This protocol basically includes a non-contrast scan of the head, followed by an arterial and a venous phase, with a single bolus and two separate acquisitions. The post-contrast scans are acquired from the circle of Willis to the symphysis pubis. The patient should be positioned, when possible, with abducted upper limbs, to reduce the radiation dose and to obtain a higher image quality of the thoraco-abdominal organs [1••, 2••, 33•, 37–40]. The IV CM

Table 1 Table summarizing characteristics of different CT imaging protocol

CT protocol after IV CM administration	Monophasic	Multiphasic	Split-bolus
Technique	Single CT acquisition (portal venous phase)	Multiple CT acquisitions (at least arterial and portal venous)	Single pass through the CT gantry after iv injection of two or three boluses of CM given sequentially, with a time delay or saline bolus between
Advantages	Adequate evaluation of parenchymal injuries and venous vessels	Exhaustive characterization of vascular (both arterial and venous) and parenchymal injuries with optimization of patient management	Contemporary acquisition of arterial and venous phases in only one scan
	Lower radiation exposure in comparison with multiphasic CT protocol		Lower radiation exposure in comparison with multiphasic CT protocol
	Lower execution time		
Disadvantages	The acquisition of only one phase may lead to misinterpret or miss vascular injuries	Radiation dose	The single acquisition may lead to misinterpret or miss some vascular injuries
			Increase of CM dose

(80–130 mL iodinated contrast medium, according to the patient's weight), at a high concentration (370–400 mg I/mL), is injected at 3.5–5 mL/s, and followed by a 40 mL saline chaser at the same flow rate, to obtain optimal vessel depiction. Automated bolus tracking identifies the arterial phase; a region of interest (ROI) is placed on the aortic arch, and arterial phase scanning starts when an attenuation threshold of 100 Hounsfield Unit (HU) is reached; depending on the speed of acquisition of the scanner it may be necessary to wait few additional seconds. The portal venous phase is performed at a 60- to 70-s delay from the beginning of the injection. As in Europe, a consultant radiologist is always present in the CT suite 24/7, she/he supervises, modifies the standard CT protocol if needed, and provides a first reading for immediate and appropriate patient management (i.e., tension pneumothorax, shattered spleen or kidney, etc). However, this approach is not uniformly applied in different countries, so the European Society of Emergency Radiology has conducted a survey to gather information about the current organization and practice of emergency radiology in Europe that will be published soon. In selected patients, an additional late phase of the abdomen and pelvis at 3–5 min may be required to differentiate arterial bleeding from lower-pressure venous bleeding, or at 5–20 min to depict urinary extravasation in patients with kidney injuries [41–43]. Furthermore, to exclude bladder injuries, irrespective of the presence or absence of pelvic fractures, it is necessary to obtain a dedicated CT cystogram. This should be obtained, in some authors' opinion, after the contrast-enhanced CT acquisitions [8•, 44, 45••], by active distention of the bladder with diluted iodinate cm through a urethral catheter (about 300–350 mL of 5% diluted contrast media) [46–49], as passive distention of the bladder during the "excretory phase" usually does not permit an overall assessment of bladder injuries [50, 51]. In patients with penetrating or gunshot injuries, a CT cystogram is particularly advised, as well as the eventual use of oral/rectal contrast administration, to exclude bladder and/or bowel perforation [52•, 53, 54]. If there is clinical suspicion of lower extremity fractures at risk for vascular injury, the CT scans are extended to the feet and at least arterial and portal venous phases are required to correctly characterize vascular injuries. The arterial phase allow to detect if a vessel injury is arterial in origin, whereas the following portal venous phase allow to establish the entity of the bleeding, orienting the management: conservative, endovascular or surgical [1••, 55, 56].

For accurate vascular and parenchymal evaluation, a slice thickness ranging from 0.5 to 3 mm, and preferably with a spacing of 0.5–1.5 mm, is recommended. Post-processing with three-dimensional (3D) multiplanar reconstructions (MPR) and volume rendering reconstructions is helpful for identifying injuries of the vessels and sites of active bleeding, as well as for searching for osseous injuries which can be missed on the axial images [42, 55–59] (Fig. 1). The availability of multiple acquisition phases in polytraumatized patients is also useful to overcome motion artifacts.

A controversial topic is the use of an unenhanced thoraco-abdominal MDCT phase, as there are published guidelines stating there is no need for unenhanced imaging of the upper abdomen [36, 60], while there are publications suggesting the added value of such an examination [61, 62], as the unenhanced initial acquisition may be useful to promptly detect hyperdense clot (i.e. the "sentinel clot sign": areas of higher attenuation near an injury site, likely to indicate the source of bleeding), to improve the detection of intramural vascular hematomas, to easily differentiate calcifications from spots of active bleeding or to simply evaluate the presence of intravascular prosthesis [42, 56, 63, 64]. However, CT dual-energy acquisitions with new scanners may offer the ability to answer these questions by generating virtual unenhanced images from the acquired post-contrast images [65].

Multiphasic protocol should be considered the "optimal" CT protocol to be adopted in high-energy trauma settings and in their follow-up [65], as the goal is the early detection and precise characterization of injuries that may affect the patient's treatment and prognosis, with a high degree of sensitivity and specificity, such as vascular injuries which may require immediate intervention [66–69]. This CT approach is commonly applied in most European trauma centers and also in the USA, whereas in other countries, as United Kingdom, the split-bolus technique is preferred. In other European centers the choice of the CT protocol for trauma is still not uniformed and may vary basing on individual center choices and on the patient's age.

CT angiography should be the first-line investigation for all patients with suspected vascular trauma without clear clinical conditions mandating immediate surgery [56, 70].

In this sense, the scan extension, from circle of Willis to the symphysis pubis, is particularly important to avoid underestimation of any kind of vascular injury, including cerebrovascular injuries, the incidence of which ranges between 1 and 3.3% of all major trauma patients [71]. The overall reported sensitivity of CT angiography for vascular cervical trauma is of 41–100%, specificity of 86–100%, and negative predictive values of 90–100% [58].

This kind of injuries may be dangerously underestimated when neck is not included in the scan, sensibly reducing the patient outcome. Indeed, early diagnosis and treatment is associated with a reduction in the rate of post-traumatic stroke [72••].

Furthermore, CT angiography is highly sensitive (86–100%) and specific (40–100%) in detecting blunt aortic injury with high positive predictive values (7–100%) and negative predictive values (93.9–100%) when compared to conventional angiography [56]. The detection and characterization of vascular injuries is more relevant and of greater clinical significance than purely detecting an abdominal solid organ injury [67] considering that the vast majority of patients are now treated non-operatively [28, 29]. Patients with arterial vascular injuries can be safely sent to the interventional radiology department for arterial stent placing (e.g., for neck vessels or aortic injuries) or embolization when appropriate (e.g., contained arterial injuries or active arterial bleeding), limiting surgery in only a small percentage of patients (e.g., with a shattered spleen or kidney, and when hemorrhage cannot otherwise be controlled). When venous injuries occur, the estimation of the bleeding entity modify the management from conservative in slight bleeding, to operative in conspicuous bleeding. In most patients, this approach has saved time and lives, significantly reducing morbidity, death from sepsis and other complications, and financial costs [73] (Fig. 1).

Regarding the abdominal vascular injuries, several studies demonstrated that the acquisition of two separate post-contrast CT phases (arterial and portal venous) increases the sensitivity and the accuracy both in splenic than in liver vascular injury detection [5••, 74–76], with a reported significant difference in the sensitivity of arterial phase in comparison with portal venous phase of 70% vs

Fig. 1 Enhanced-CT of a 54 years old male patient underwent major trauma: arterial phase in axial plane, MIP reconstruction (**a**), arterial phase in coronal plane (**b**) and portal venous phase in coronal plane (**c**). Note the absence of hemoperitoneum and the presence of two pseudoaneurysms at the inferior pole of the spleen (**a**, **b** arrows) only evident in the arterial phase of study. These lesions cannot be depicted in the portal venous phase (**c**)

17% for the detection of intrasplenic pseudoaneurysm [74]. In data reported by Uyeda et al. [76], 46% of patients with contained vascular injuries were identified only during the arterial phase of image acquisition; similarly, Melikian et al. found dual-phase CT was more sensitive (80.0% vs. 37.5%, $P = 0.016$) and more accurate (76.2% vs. 37.5%) than single phase imaging for diagnosing splenic vascular injury [75]. About liver vascular injuries, our previous published data [5] similarly shown that in 71.5% of patients it was possible to detect contained vascular injuries exclusively in the arterial phase of the CT study, and adequately characterize active bleeding from an arterial origin in 76.9% of cases. This has important management implications.

MDCT Assessment of Bleeding in Trauma

Bleeding represent the most common cause of preventable death in trauma patients, being responsible of about 40% of death [77].

In blunt trauma patients, bleeding is mainly related with stretching mechanisms on the vessel wall. These kind of injuries may be clinically silent until patients conditions become critical with hemorrhagic shock [1••].

So, one of the main goal of CT in trauma is to identify, quantify and characterize the bleeding or the presence of vascular injuries at risk for bleeding, to ensure the best patient's treatment.

Active bleeding is seen as the presence of extravasated contrast agent, and it may be classified into three main categories according to its size and morphology: a spot (punctiform self-limiting bleeding), a jet (linear bleeding with no significant morphological change), or pooling (active extravasation of contrast media, with significant change in its shape and volume over multiple phases of acquisition) [78].

Multiplanar Reformations (MPR) and Maximum Intensity Projection (MIP) can help in revealing the bleeding vessel of origin and the severity of hemorrhage.

To properly detect active bleeding, a rapid rate of IV CM injection, and high iodine concentration are suggested. This is as the degree of arterial vessel contrast enhancement is directly affected by the contrast medium delivery rate and from their concentration, so a faster delivery increases the magnitude of the aortic enhancement [79].

If an active bleeding is firstly seen in the arterial CT phase, it can be defined as arterial in origin, but it should be also considered that arterial active bleeding can be seen in the portal venous phase in patients with hemodynamic alterations, or due to arterial spasm that limits the bleeding.

From a therapeutic point of view, the importance of the active bleeding depends on its severity and origin, as not all the active bleeding need to be operatively managed in an emergency setting. Slight active bleeding, especially if intraparenchymal and of venous origin, may be self-limiting and conservatively managed [5••]. If only a single phase is acquired, it is not possible to adequately evaluate and separate clinically relevant arterial bleeding from other less relevant sources of bleeding.

Contained Vascular Injuries

The use of a MDCT multiphasic protocol permits the differentiation of contained bleeding injuries from actively bleeding injuries [5••, 80••].

Contained vascular injuries (i.e., intimal tear, intramural hematoma, pseudoaneurysms and arteriovenous fistulas) can generally be safely treated non-operatively, with stent-grafts or by embolization; conversely, if untreated, these injuries may increase in extension, in volume and occasionally in number, and can rupture causing active bleeding [1••, 5••, 80••]. In patients with contained vessel injury, MPRs and MIP images can be useful to provide crucial information to the interventional radiologist and/or surgeon, which is necessary for planning therapeutic intervention.

The main drawback of the multiphasic MDCT protocol for trauma is related to the radiation dose as a consequence of the multiple acquisition phases. Indeed, the reported radiation dose reduction between split-bolus whole-body CT and multiphasic CT protocol is between 31.9 and 68.1% [72••, 81].

However, given the greatly increased morbidity and mortality associated with vascular injuries, and the possibility that, especially young trauma patients are able to compensate until sudden shock occurs, the additional radiation dose should not discourage acquisition of multiple phase images [82]. In this sense, the introduction of iterative reconstructive techniques into CT imaging may led to a decrease in whole-body CT dose, from 15 to 20 to 5–10 mSv [83] as well as the adoption of dual-energy CT, that may lead to radiation doses lower than those for single-energy CT, also considering that virtual non-contrast images can be retrospectively created from post-contrast dual-energy CT acquisitions [65].

Split Bolus CT Protocol

Due to the larger adoption of MDCT in trauma patients, usually involving young population, and the associated non-negligible radiation dose, efforts have been made to try to reduce the radiation dose. In this sense, several authors are studying the adoption of a split-bolus MDCT protocol [31, 34, 36, 64, 71, 81, 84–87]. This CT protocol consists in a single pass through the CT gantry after iv injection of two or three boluses (arterial and portal venous) of CM given sequentially, with a time delay or saline bolus between [33•, 72••, 81]. The sequential contrast boluses result in a single acquisition, reflecting the combination of arterial and portal venous phases (and potentially a urinary excretory phase) [72••].

Among the more recent studies on this topic, Hakim et al. [88] compared the image quality of conventional arterial and portal venous phase CT with two biphasic injection protocols in poly-trauma patients consisting in the injection of 65 mL contrast medium at a rate of 1.5 mL/s; after completion at 43 s, a second 65 mL contrast bolus was started at a rate of 3.5 mL/s followed by a single spiral acquisition, at approximately 60 or 70 s. The authors found comparable image quality with less radiation and reduction in acquisition time.

Marovic et al. [84] in a study focused on splenic injuries in a cohort of 36 split-bolus trauma CT examinations, found that splenic image quality was diagnostic in all cases, however, in comparison with Digital Subtraction Angiography (DSA) in the diagnosis of active arterial hemorrhage and splenic pseudoaneurysm, split-bolus protocol had significantly lower sensitivity, of 50.0% and 38.9% respectively.

Godt et al. [71] compared the image quality and injury findings of a portal venous phase CT with those of a triple-split-bolus CT protocol as follow: first bolus consisting in 20 mL of intravenous contrast medium followed by a 30-mL saline chase, both at a flow rate of 3 mL/s. At least 5 min after, the second bolus of 100 mL contrast media is injected at a flow rate of 5 mL/s, followed by a 45-mL saline chase (flow rate 6 mL/s). After a delay of 32 s, the third bolus of 55 mL contrast medium is administered followed by a 55-mL saline chase, both injected at a rate of 5 mL/s. Hereafter, the CT scan was initiated by manual bolus tracking with the region of interest (ROI) in the descending aorta. They found the triple-split-bolus CT protocol achieved better contrast enhancement, equal performance in organ injury diagnosis, and similar image quality compared to the portal venous CT protocol, however, no vascular injuries were detected in the study population.

All the studies investigating images quality for abdominal split-bolus single-pass CT found an adequate images quality with higher parenchymal enhancement and lower arterial enhancement than conventional CT protocol. The reason for the higher enhancement of parenchymal organs is probably related to the higher amount of contrast medium and, consequently, of the iodine dose applied in all split-bolus protocols [71]. This lead to the suggestion in these protocol to adopt contrast media with lower iodine concentration (300–360 mg I/mL) [88] or differently set an adequate windows setting.

There are no doubts that the split-bolus single-pass approach is superior to the single bolus single-pass CT, and that the parenchymal enhancement adopting split-bolus protocol is adequate, but the main problem remains the identification and characterization of vascular injuries. For their depiction, a greater contrast between arterial vessels and the surrounding parenchyma is needed, and further a subsequent venous phase to evaluate the stability or the presence of active bleeding, as this significantly affects therapeutic management. So, the main limitation of this technique remains the possible inadequate detection and characterization of vascular injuries and the possible difficulties in distinguishing vascular injuries from pre-existing parenchymal finding. There are still no studies that adequately explored this point; for this reason, several authors, Hakim et al. [88], Godt et al. [71], and Leung et al. [81], prefer to avoid potential difficulties in differentiating parenchymal and vascular injuries and contrast leakage from ureteral or bladder injury, adopting, in seriously injured patients, the conventional single-bolus dual-phase CT protocol.

Conclusion

Due to the high sensitivity and specificity of MDCT for injuries detection and characterization, and short execution time, in the last years a rapid increase in the number of whole-body CT examinations in trauma patients has been observed. So, different CT protocols were investigated attempting to reduce the radiation exposure in a predominantly young population. However, currently, the only protocol ensuring a complete characterization on injuries modifying patient's management is still the multiphasic CT study. Therefore, efforts must be made in adequate patient selection and technological advancement rather than in the reduction of scans potentially useful in identifying parenchymal and vascular damage.

Compliance with Ethical Guidelines

Conflict of interest The authors declare no conflicts of interest pertaining to this article.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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