Chapter 1
Postmortem Computed Tomography (PMCT) Scanning with Angiography (PMCTA): A Description of Three Distinct Methods

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Introduction

Postmortem computed tomography (PMCT) is rapidly becoming a standard investigation in many mortuaries around the world. Arguments remain as to the relative merits of PMCT in comparison to traditional invasive autopsy, but there are few who would argue that PMCT has no role in the investigation of death, particularly for unnatural death.

For an imaging system to be clinically useful, it has to identify different tissues, pathologies, or objects as different; this can be referred to as "contrast resolution." This discrimination must also be in time and space (temporal and spatial resolution). The speed of scanning and spatial resolution (to identify small pathologies such as subtle bone fractures) is important, but contrast resolution is the key; if pathology cannot be distinguished from normal tissue, then there is little to gain. For basic applications this is not a problem as radiographic contrast for soft tissues is based mainly on tissue density (or more precisely electron density) and is easily

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sufficient to spot metallic foreign bodies, discern bone from soft tissues, soft tissues from fat, and all structures from air. Therefore, standard radiography and fluoroscopy are sufficient to identify metallic foreign bodies and bone fractures, and indeed these were the mainstay of postmortem imaging for many years until the development of CT imaging in the 1970s [1]. CT scanners offer the ability to reconstruct single slices of information from a body, rather than to accept a radiograph showing a summation of the whole body part. This ability to omit the overlying structures leads to a significant increase in contrast resolution, although the underlying mechanism of contrast is the same. This slice-by-slice approach also allows a better spatial awareness of abnormalities in three dimensions.

PMCT was first reported in 1983 [2], and in 1994 it was proposed that CT could prove a possible replacement to the autopsy in trauma cases [3]. This led to similar proposals for magnetic resonance imaging (MRI) [4] and for children [5]. MRI has been increasingly used for forensic imaging both in the living [6] and in the postmortem setting [7] and, for most body parts, demonstrates better contrast resolution than CT. A major clinical weakness of MRI—its sensitivity to cardiac or respiratory motion—is not a problem in postmortem (PM) use. However, MRI does have other key weaknesses that hold it back as a routine PM imaging tool: the cost is high, the equipment is much more technically demanding to operate, there are safety issues relating to the strong magnetic fields required, scan times are longer, and MRI has lower "spatial" resolution than CT, losing the fine detail required for bone trauma and lung imaging.

Recently PMCT has started to advance more rapidly for two key reasons: Firstly there has been a global increase in use and availability of scanners, causing subsequent decrease in their relative costs, and secondly the advent of multi-slice CT (MSCT). MSCT is not critical for the performance of PMCT, and interestingly one of the major advantages of MSCT in clinical practice is speed, which for PMCT just makes whole body scanning more convenient. However, MSCT does considerably improve the ability to reconstruct the axially acquired CT data into any plane desired (multi-planar reconstruction, MPR) and to create three-dimensional (3D) reconstructions, which can substantially improve the recognition and demonstration of pathology, particularly trauma. There have also been advances in the engineering of CT scanners that have allowed them to be easier to operate and to scan large volumes at high resolution without overheating. Only 25 years ago scanning a whole body in 2 mm increments would take well over an hour. This was reduced to about 10 min in the late 1990s with spiral CT (at low power) but can now be achieved in less than a minute with increments of 0.5 mm.

Due to these factors the world woke up to this possibility. Driven initially by the work of the Virtopsy® group in Switzerland [8, 9] and the eventual introduction of dedicated CT scanners into mortuaries, such as in Scandinavia and the Victorian Institute of Forensic Medicine, Australia, in 2005, the interest, experience, and research evidence base has grown. Publications are now increasing from all around the world with cooperative groups being formed such as the International Society of Forensic Radiology and Imaging (ISFRI) [10] and Technical Working Group Postmortem Angiography Methods (TWGPAM) [11]. Most recently international standards of nomenclature for publications and research have been put forward [12].

This article concerns a key and crucial development for PMCT. Although PMCT shows definite advantages over standard radiography, it still struggles to detect more subtle disease [13–15]. In clinical practice, CT is used as an adjunct to the investigation and management of the patient rather than a single diagnostic tool, and also PMCT is more difficult to interpret than clinical CT, as changes occur rapidly during and after death that can obscure existing pathology. These include edema occurring in many tissues and subsequently the appearance of gas [9]. Even in clinical CT, pathology may only cause subtle changes in tissue appearance, and it is for this reason that routine body and brain clinical CT scanning is normally "enhanced" using contrast agents that can be imbibed, injected, administered by enema, or persuaded down fistula tracks. These contrast agents alter the attenuation of an X-ray beam to make tissues appear different, relating to the distribution of the agent.

A Brief History of Angiography

The study of blood vessels and lumens of other tubes by specific opacification predates radiology and goes back to the beginning of the sixteenth century, when scientists such as Leonardo da Vinci and Jakobus Berengius studied the human body. In order to investigate the interior of hollow anatomic structures, they produced wax casts of the heart chambers and the cerebral ventricles by using maggots to remove the surrounding tissues after wax injection [16, 17]. During the seventeenth and eighteenth centuries, direct vascular injections were performed by pioneers such as de Graaf, Ruysch, Lower, and Virchow [16, 17]. The resulting vascular casts were sufficient for detailed study of the anatomy of the vascular system.

Radiopaque contrast agents were therefore developed very quickly after the discovery of X-rays in 1895. In 1896 in Vienna, Haschеck and Lindenthal demonstrated an angiogram on an amputated hand using injection of Teichmann's mixture (a mixture of lime, mercury, and petroleum) [18], and such angiographies were common by 1899 [16]. Although these early contrast agents were toxic, this did not hold back their use in cadaver studies. The use of postmortem angiography techniques to investigate the vascular supply of organs, especially the heart, became then a real boom, particularly during the first half of the twentieth century. At this time, numerous methods and injection materials existed, and all kinds of organs had been investigated in order to understand their vascular anatomy. However, by the end of the twentieth century, the use of postmortem angiography had nearly vanished, without any visible reason. Only some rare articles appeared, describing the investigation of specific parts of the vascular system such as esophageal veins [19], coronary arteries [20], intracranial arteries [21], and spinal arteries [22].

As early as 1927, Moniz performed the first cerebral angiograms in living patients, using sodium iodide under sedation, and many feel it was this, rather than the now discredited prefrontal leucotomy, that should have earned him his Nobel prize in 1949 [23]. From the 1930s to 1950s, water-soluble iodine agents, based on pyridine and then benzene rings, were developed that were reasonably well

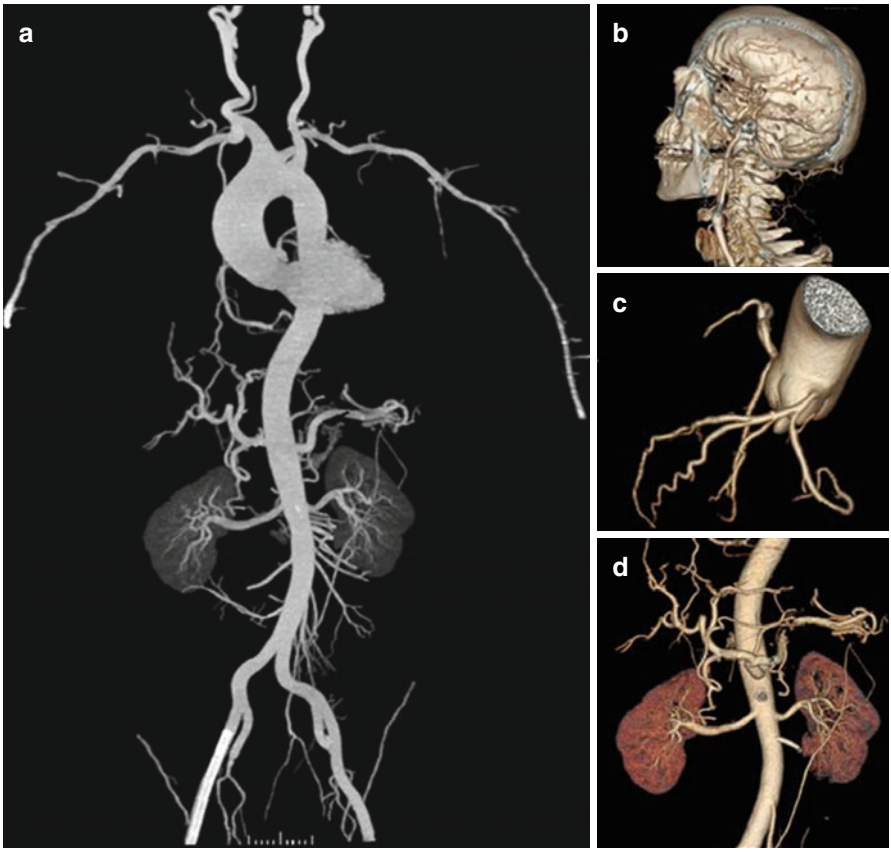

Fig. 1.1 Arterial phase of whole body PMCTA using oily contrast agent with maximum intensity projection (MIP) showing the arteries of the thorax and abdomen (**a**) and 3D volume rendering reconstructions of the cervical and intracerebral arteries (**b**), coronary arteries (**c**), and the major abdominal vessels and both kidneys (**d**) (Images courtesy S. Grabherr, Lausanne, Sz)

tolerated and could be injected into the venous system and excreted by the kidneys. These allowed both angiographic studies [24, 25] and also assessment of organ enhancement, such as intravenous urograms (IVUs) to study both kidney anatomy and function [26]. These were relatively high osmolar agents, but low osmolar compounds were developed and latterly introduced in the 1990s.

Therefore, in postmortem practice most approaches had been direct, using ex vivo organs such as for the heart [27], because enhancing the vascular system for a PMCT scan is more challenging due to the lack of an intact circulation. In clinical practice the contrast is injected, and the circulation then takes it all around the body. Radiologists are used to directly injecting contrast media into specific arteries and veins using intra-arterial or intravenous catheters, but many would be surprised that widespread arterial or venous contrast opacification could be achieved in a cadaver (Fig. 1.1). However, this would be of no surprise to embalmers going back centuries!

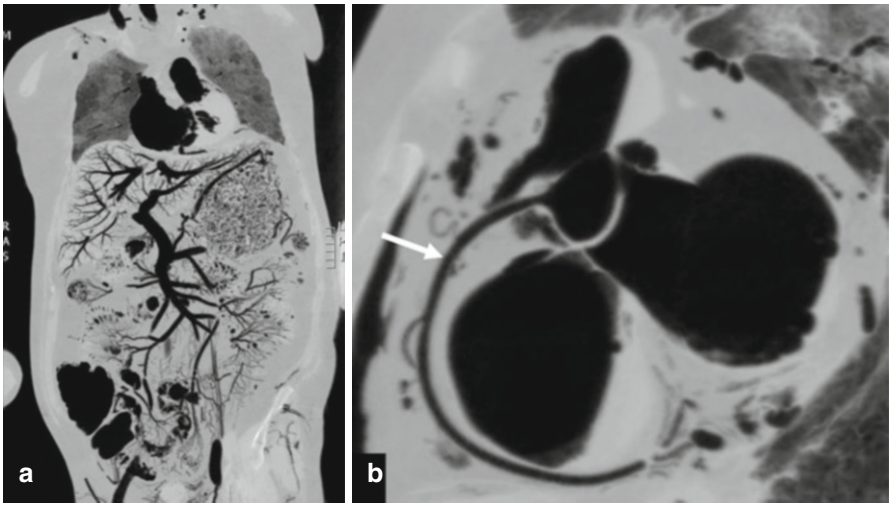

Fig. 1.2 The use of air as a negative contrast agent for PMCTA, demonstrating a "whole body" approach via catheters in the femoral vessels (**a**) and a targeted coronary approach (**b**) showing a patent right coronary artery (*arrow*) (Images courtesy of Morgan B & Rutty G, University of Leicester)

This chapter is the story of how arterial and venous contrast studies have been developed and how PMCT has been developed to PMCTA.

Contrast Agents

Any substance that alters the attenuation of an X-ray beam can be considered a contrast agent. We traditionally consider these to be agents that increase attenuation, appearing white (positive) on traditional CT images. These agents generally use substances that have a high atomic number, which increase attenuation of X-rays due to their density and the photoelectric effect. Therefore, relatively low concentrations of iodine solution or barium can have dramatic effects on the image.

The various types of contrast agent used in postmortem work have been summarized [17] and include corpuscular preparations such as barium sulfate, where the particles are suspended in water [28] or gelatin/agar [29]; lipophilic agents dissolved in oily liquids generally using iodine; casting techniques, possibly using a silicone rubber and lead oxide [30]; and the water-soluble iodinated chelates generally used in clinical imaging practice. However, an agent does not have to attenuate X-rays (positive contrast agent) in this manner to be useful. Clinically agents such as air or fat that lower the attenuation and appear black on traditional CT images are also used to improve contrast in a "negative" manner (Fig. 1.2).

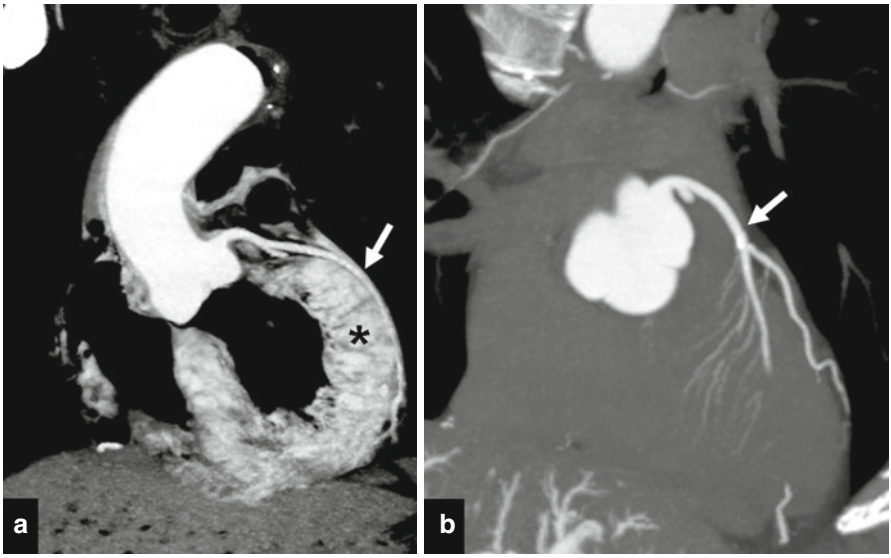

Fig. 1.3 A comparison of normal coronary artery and left ventricle studies by water-soluble contrast agent (**a**) and oily contrast agent (**b**). An opacified patent left anterior descending artery is shown in both cases (*arrow*). However, using water-soluble contrast agent leads to rapid leak of the contrast into the extracellular extravascular space (*). This is a key aspect of clinical contrast-enhanced imaging but may cause edema in the tissues if a lot of contrast is used, such as in whole body techniques, which may affect histology. Also the rapid dispersion diminishes vascular contrast requiring rapid imaging after injection (Images courtesy of Morgan B & Rutty G, University of Leicester)

While casting techniques are mostly only applicable on single organs, methods were developed to render visible the whole vascular system of a body, such as for investigating the vessels of human embryos and fetuses [19] and newborns [31]. Most methods used a simple manual injection via a syringe to introduce the contrast agent into the vascular system. Many recommendations were provided on how to perform the perfusion of single organs [17], but there were few in the last century regarding the perfusion of whole bodies. An exception is the article written by Stoeter and Voigt [19], which describes a radiologically controlled, discontinuous injection of the contrast agent, with angiography performed in the intervals.

All of these agents have their advantages and pitfalls. The key issues, whether using a corpuscular agent in suspension, an oily agent, or water-soluble agent, are related to their molecular size, viscosity, density, and osmolality, which all dictate how they disperse in the body (pharmacokinetics) (Fig. 1.3). In addition some agents such as the barium suspensions have properties that allow them to coat the walls of vessels, providing exquisite wall detail especially if the lumen is subsequently filled with a negative agent such as air. These factors will be discussed further for the techniques in the following sections.

Whole Body Infusion Angiographic Techniques in Switzerland

In 2005 Jackowski et al. from the Institute of Forensic Medicine, University of Bern, Switzerland, reported preliminary results of a new technique of minimally invasive whole body PMCTA using meglumine-ioxithalamate as a contrast agent and a roller pump, which enabled stable conditions for the injection of the contrast agent [32]. This water-soluble contrast agent solution provided excellent vessel visualization but caused tissue edema and artifacts in histological investigations when injected using their protocols, which rendered its application in medicolegal cases difficult. This was probably due to the rapid extravasation of these agents into the extravascular extracellular space and their high osmolality. In order to overcome the extravasation into the surrounding tissue, and therefore the massive edema caused, polyethylene glycol was added as a solvent [33].

At the same time the group in Bern and then Lausanne, Switzerland, started to devise a system that could deliver a postmortem circulation to resemble in vivo conditions and allow the perfusion of the body [34]. A first feasibility study, performed on an animal model, showed the success of the concept, with the use of diesel oil as a perfusate and a roller pump as perfusion device [35]. A postmortem circulation was established in adult dogs and cats. The oily contrast agent Lipiodol® Ultra-Fluide (Guerbet LLC, Bloomington, IN) was then injected during which perfusion imaging was performed at defined intervals giving a dynamic arterial, "parenchymal," and venous phase. Oily perfusates will remain intravascular, avoiding extravasation into the surrounding tissue causing edema [36, 37], and the images in the "parenchymal" dynamic phase will be different to those achieved using standard water-soluble contrast agents as the contrast does not enter the capillaries or leak into the tissue parenchyma. To adapt the technique to a human model, two essential changes were made: The perfusion device was changed from a roller pump to a modified heart-lung machine, and diesel oil was replaced by the odorless oil paraffinum perliquidum. The resulting technique was called "two-step postmortem angiography" [34], as it consisted in the establishment of a postmortem perfusion in a first step and the injection of contrast agent with simultaneous image acquisition as a second step. The obtained images displayed the vascular anatomy in detail, up to the level of arterioles. Vascular lesions such as chronic occlusion and traumatic vessel rupture could be detected [34, 38]. The major problem of the technique was the appearance of a discharge of the perfusate into the stomach and the intestine. This finding was not surprising given the combination of bacterial decomposition and autolytic activities that occurs in the gastrointestinal tract, which may lead to an early increase in vascular permeability in this region [35]. This weakness was also criticized by Ross et al. [39] who compared the application of an oily approach to the one proposed by Jackowski et al. [32]. The advantages of using oily liquids have been described [35]. Microscopic studies show that the oil blocks the capillaries due to fatty embolism, which are especially vulnerable to postmortem increases in permeability. The same principle is used in chemoembolization for cancer treatment by using chemotherapy in an oily medium, which is arrested in the small tortuous

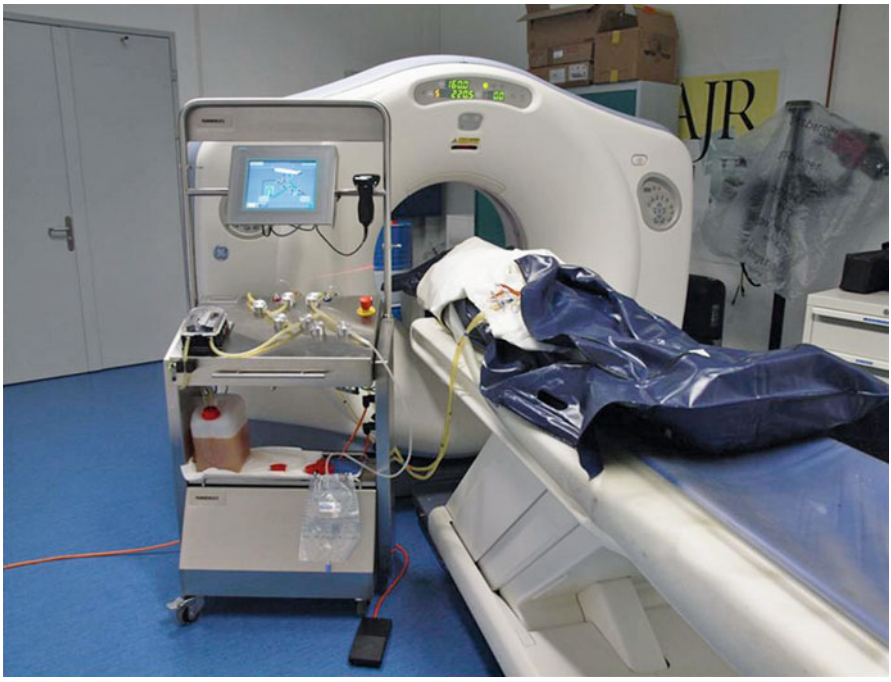

Fig. 1.4 Setup for whole body PMCTA showing the investigated body on the CT table; connected via the cannulas and perfusion tubes to a Virtangio® perfusion device (Images courtesy S. Grabherr, Lausanne, Sz)

neo-angiogenic vessels of a tumor thereby allowing higher exposure of the tumor to chemotherapy with less systemic exposure [40]. In the postmortem setting, the oil passes to the venous system through arteriovenous shunts. The level of this micro-embolization depends on the viscosity of the oily perfusion, which can be varied depending on what characteristics are required.

In the University Centre of Legal Medicine in Lausanne, Switzerland, a research group was created with the aim to develop these contrast agents and perfusates for PMCTA and to establish an easily applicable standardized protocol to achieve complete filling of the vascular system and decrease artifacts to improve diagnostic quality. In 2011, the group published their first study of 45 human cases using different perfusion protocols [41] calling their technique MPMCTA (multiphase postmortem computed tomography angiography). They used a perfusion device (Virtangio®, Fumedica AG, Sz) using a single-use set containing tube sets and cannulas inspired by the modified heart-lung machine, first used by Grabherr et al. in 2006 (Fig. 1.4) [35] and later by Ross et al. in 2008 [39]. A new oily contrast agent mixture (Angiofil®, Fumedica AG, Sz) was specifically developed by the research group for postmortem investigations [17, 38]. Chemically, the contrast agent Angiofil® is a mixture of esters (mainly ethyl esters) of polyiodinated fatty acids. It is yellowish, nearly odorless, and stable under normal conditions (room

temperature). As opposed to diesel oil [35] or paraffinum perliquidum [34], the contrast agent Angiofil® is dissolved in the more viscous paraffin oil (paraffinum liquidum). By changing the viscosity of the perfusate, extravasation into the gastrointestinal tract has virtually disappeared. By diluting Angiofil® with a solvent such as decane, its viscosity can be decreased so as to enter the capillaries to enable microangiography [42].

The study suggests the use of high perfusion volumes as well as the recording of at least three angiographic phases and a native CT scan. The standard protocol of MPMCTA consists therefore in the performance of one native CT scan followed by the cannulation of the femoral vessels of one side of the body. During the cannulation process, blood samples are collected for toxicological and biochemical analysis. Once these samples are done, contrast agent mixture composed of 6 % of Angiofil® and paraffin oil (paraffinum liquidum) is infused. The contrast (1,200 ml) is injected into the femoral artery at a flow rate of 800 ml/min prior to "arterial phase" image acquisition; 1,800 ml is then injected (800 ml/min) prior to "venous phase" image acquisition. Then a further 500 ml of contrast is injected at a flow rate of 200 ml/min to perform the "dynamic phase" image acquisition.

By using the technique of MPMCTA, the whole vascular system of the head, thorax, and abdomen is visualized (Fig. 1.1). The only exceptions comprise parts of the cerebral sinus and vessels, which may be occluded by large postmortem clots. In contrast to the earlier techniques using oily liquids, this method did overcome the problem of discharge of the perfusate into the stomach and the intestine, which was only slight, even in cases with a long time gap between angiography and autopsy. Further visualization of all vessels was possible without changing the position of the body, as proposed by Ross et al. [39]. Using three distinct phases of contrast is helpful to avoid misinterpretations, which may occur if only arterial and venous phases are performed [41]. This is similar to other dynamic diagnostic imaging tests, such as intravenous urograms and barium studies, where an abnormality should be consistent to be interpreted as a real finding.

The use of MPMCTA has increased in the last few years and has already been introduced as a routine investigation for medicolegal purposes in addition to conventional autopsy in many centers. Different studies have been performed investigating the advantages and inconveniences of MPMCTA compared to autopsy [43], technique-related artifacts [44], its performance compared to clinical in vivo CT angiography [45], its influence of biochemical markers [46], as well as its use for investigating different medicolegal case groups such as cases of sudden cardiac death [47] and coronary thrombosis [48] and cases of fatal outcome after surgical interventions [49].

The introduction of MPMCTA into medicolegal death investigation improves the accuracy of the postmortem exam compared to nonenhanced (native) PMCT alone and in some situations may even improve on conventional autopsy. For example, MPMCTA is more likely to detect a source of hemorrhage than conventional autopsy, even when not detected by premortem clinical CT angiography (Fig. 1.5). For these cases, the combination of conventional autopsy and MPMCTA has already been proposed as being a new gold standard.

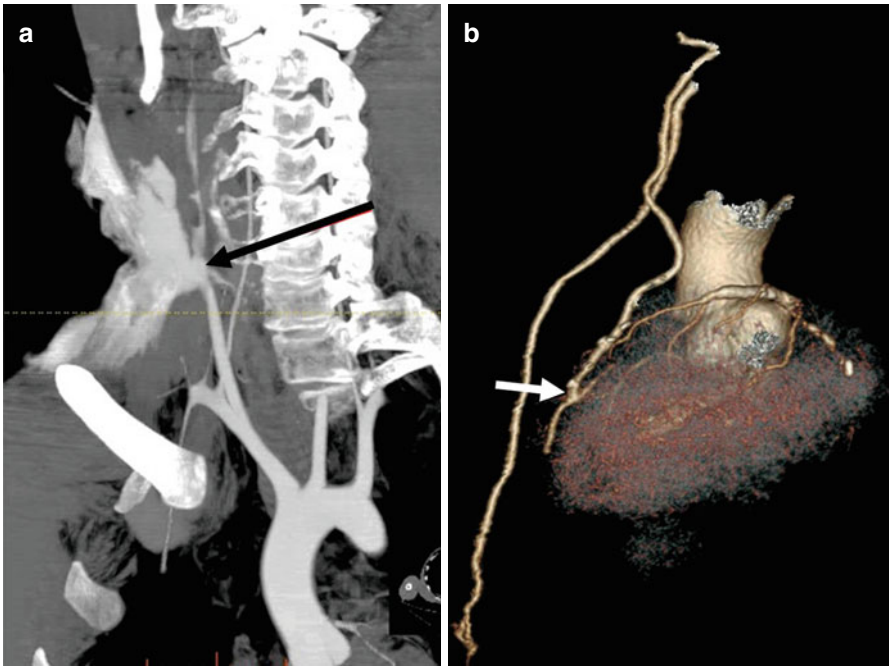

Fig. 1.5 Adult suicide using a knife. (**a**) An MIP image of arterial phase whole body PMCTA using oily contrast agent showing massive leakage of contrast agent from the right common coronary artery (*arrow*) and (**b**) 3D volume rendered image demonstrating an intact coronary bypass between the left internal mammary artery and the left inter anterior descending artery (*arrow*) (Images courtesy S. Grabherr, Lausanne, Sz)

PMCTA Using Cardiopulmonary Resuscitation (CPR) to Establish Circulation in Japan

In Japan, due to a very low rate of conventional autopsy and the highest distribution of CT scanners per population in the world, postmortem computed tomography (PMCT) is performed in more than 20,000 cases yearly [50]. The majority of these cases involve screening for unusual causes of death in patients brought into emergency rooms (ERs) in a state of cardiopulmonary arrest, where resuscitation was unsuccessful.

For PMCT, the Japanese experience is similar to other reported studies, showing that PMCT alone can give a cause of death in 30 % of cases of nontraumatic death, and is especially useful in hemorrhagic cases, including cerebral hemorrhage, aortic dissection, and aortic aneurysm rupture [51, 52]. However, as previously stated, ischemic heart disease is a factor in more than half of sudden and unexpected deaths in Japan, which is difficult to detect with PMCT. Therefore, a diagnosis of ischemic heart disease is made after review of clinical history, examination findings such as ECG, and the presence of pulmonary edema, an indirect PMCT finding suggesting

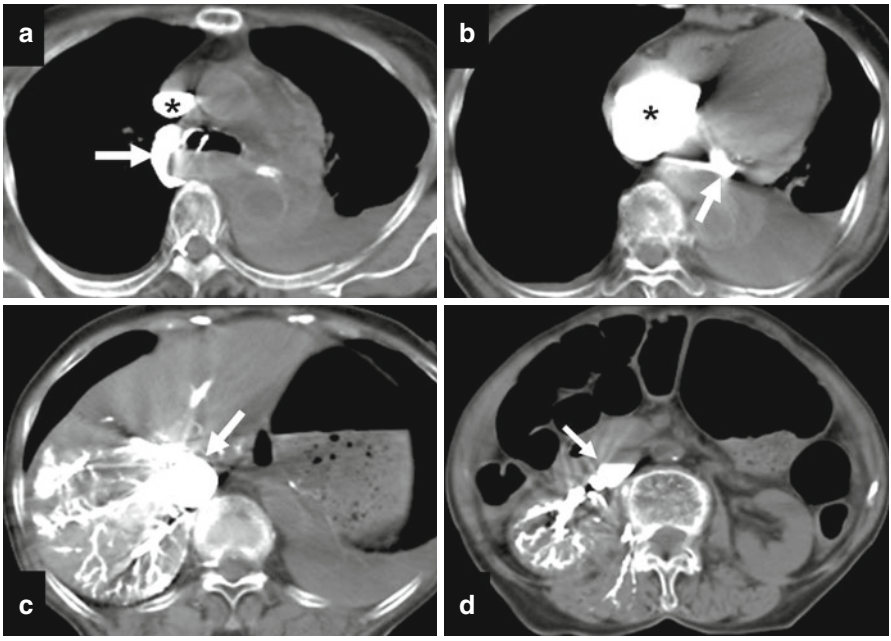

Fig. 1.6 PMCTA without using the CPR method in an 80-year-old female after a traffic accident. The contrast media infused via an intravenous catheter moved from the right brachiocephalic vein to the superior vena cava and right atrium (*), and refluxes into the azygous vein (**a**) and coronary sinus (**b**) (*arrows*), IVC and abdominopelvic venous system (**c**, **d**). Without CPR venously injected contrast media do not pass through the cardiopulmonary circulation (Reprinted with permission from Ezawa and Shiotani [72])

acute left heart failure [53]. It is also difficult to diagnose pulmonary thromboembolism with non-contrast PMCT.

The whole body and targeted PMCT angiography (PMCTA) techniques described in this chapter are customarily difficult to do in Japan where surgical management on a newly deceased patient is traditionally shunned. Instead, quite a few Japanese hospitals conduct PMCTA using a less invasive and relatively simple technique that can be simply done in a CT examination room in ordinary hospitals [54, 55]. The administration of contrast agent from the peripheral venous route alone does not provide diagnostically useful angiograms (Fig. 1.6), but PMCTA is possible in combination with chest compressions. Chest compression during cardiopulmonary resuscitation (CPR) increases blood pressure to a certain degree and generates cardiac output of approximately one-fourth compared with the normal state [56]. This phenomenon makes possible PMCTA with chest compression (CPR method). The contrast media is normally injected into an arm vein such as the cubital vein in the antecubital fossa; it enters the right atrium and moves into the right ventricle, pulmonary artery, pulmonary vein, left atrium, left ventricle, and aorta and then into the arterial tree including the proximal portions of the cerebral, coronary, celiac, and superior mesenteric arteries (Figs. 1.7 and 1.8). The PMCTA

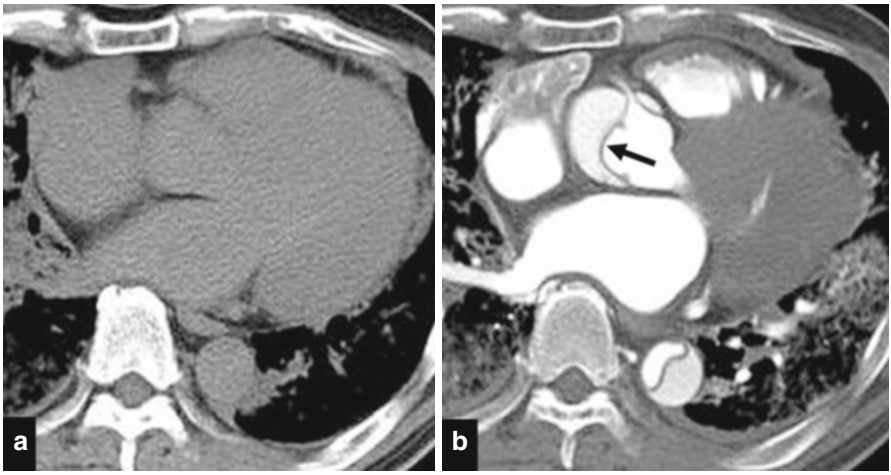

Fig. 1.7 PMCT (**a**) and PMCTA using the CPR method (**b**) in a 60-year-old male showing an intimal flap in the ascending aorta (*arrow*) due to aortic dissection (Images courtesy of Sakamoto N & Shiotani S, Tokyo, Japan)

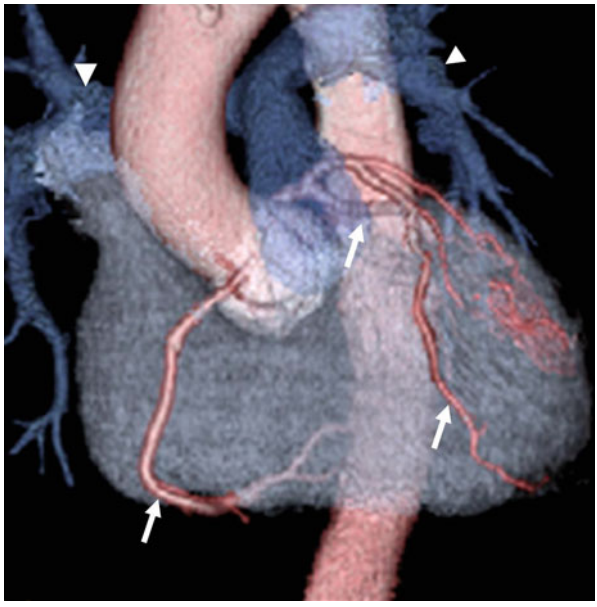

Fig. 1.8 PMCTA using the CPR method with 3D image reformats showing coronary (*arrows*) and pulmonary arteries (*arrowheads*) (Image courtesy of Sakamoto N & Shiotani S, Tokyo, Japan)

scan can therefore be performed immediately after death. This is helpful as in the Japanese experience, there is little extravasation of the contrast media within the 3-h period after death, but this increases thereafter, due to increasing postmortem vascular permeability.

The cases shown in Figs. 1.7 and 1.8 are patients arriving at the ER of Tokyo Medical Center in a state of cardiopulmonary arrest (CPA) with failed resuscitation.

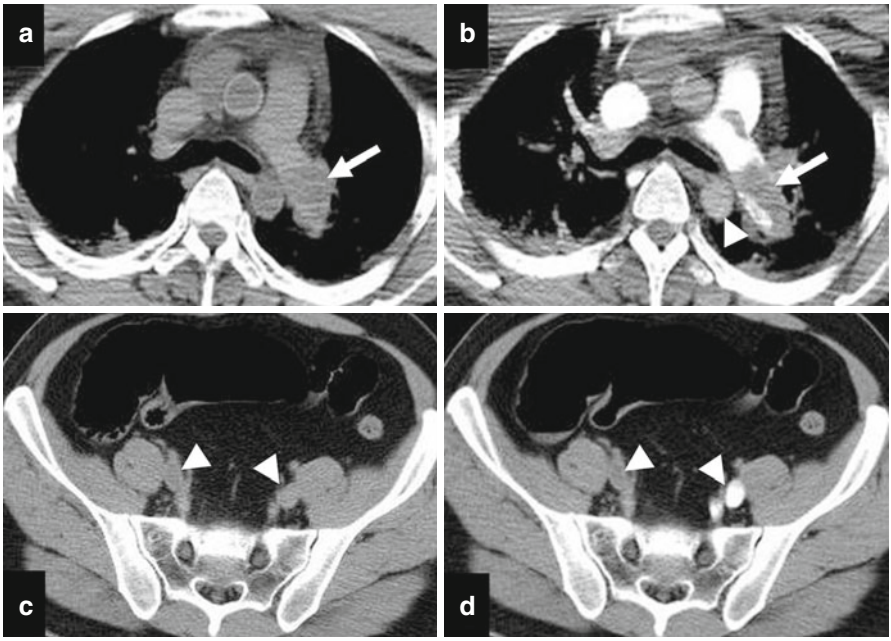

Fig. 1.9 PMCT (**a**, **c**) and PMCTA using CPR method (**b**, **d**) in a case of pulmonary thromboembolism in a male in his 40s showing an embolus in the pulmonary artery (*arrow*) and no contrast in the aorta. Pelvic images (**c**, **d**) show failure of filling of the right common iliac vein despite filling on the left (*arrowheads*). Despite this demonstration, thromboembolism remains a difficult problem for all PMCTA techniques due to variable presence of postmortem clot (Images courtesy of Sakamoto N & Shiotani S, Tokyo, Japan)

After confirmation of death, consent to perform non-contrast PMCT and PMCTA was obtained from the family of each subject. An automatic injector is used with the intravenous catheter already in place after cardiopulmonary resuscitation. Standard clinical contrast media are used at similar strengths and volumes to normal clinical CT practice, e.g., 2 ml/kg, up to 150 ml, at a rate of 1–2 ml/s. While injecting the contrast media, chest compressions are done for 2 min at a rate of 100 times/min (a total of 200 times). If on scanning passage of contrast is deemed insufficient, 200 or fewer additional chest compressions are done. However, if the total number of chest compressions exceeds 400, image contrast is degraded due to the widespread contrast media. Invasiveness to the cadaver is minimal, as only about 2 min of chest compression is done after death, compared with approximately 30 min of chest compression during the failed resuscitation management in the emergency room. In cases where chest compression cannot be effectively done, such as a multiple rib fracture case, contrast enhancement is insufficient due to lack of effective perfusion of the media in the body.

This CPR method of PMCTA allows diagnosis of arterial and occasional venous based pathology. Fig. 1.9 shows a case of filling defects in the pulmonary artery and right common iliac vein with failure of passage on contrast agent into the aorta

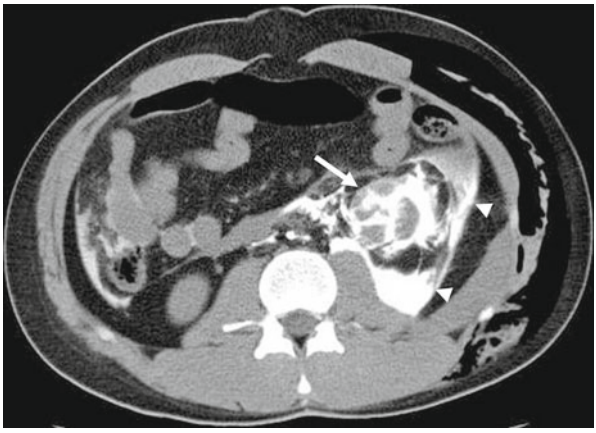

Fig. 1.10 PMCTA using CPR method in an 30-year-old male after a traffic accident showing left kidney trauma (*large arrow*) and leak into the perirenal space and retroperitoneum (*arrowheads*)

because thromboemboli hinder its passage. Using this technique it is assumed that these filling defects are not due to postmortem clot as the scans are performed early and a large quantity of tissue plasminogen activator is secreted from the vascular endothelium during sudden death, thereby increasing blood fluidity.

In cases where blood loss volume is large due to hemorrhage, CPR does not establish effective circulation and contrast enhancement of the arterial route is insufficient and reflux to the veins increases [57]. This can be useful in trauma cases as it may show organ injuries as extravasation of the contrast media (Fig. 1.10).

Targeted Coronary Angiography Techniques in the UK

There is a requirement that a medical cause should be given for all deaths in England and Wales [58]. The medical professional attending the final illness often does this, but may not be able to in cases of sudden unsuspected death. Therefore, about 45 % of cases are referred to Her Majesty's (HM) Coroner, who will often request a post-mortem investigation, normally by autopsy, to establish the cause of death, even when obviously from natural causes. A considerable number of these deaths will be due to cardiac and particularly coronary vascular disease.

Therefore, without the ability to diagnose coronary artery disease (CAD), the most common cause of non-suspicious sudden death in our population, PMCT may only be able to make a diagnosis confidently in 28–41 % of cases [13], such as for catastrophic hemorrhage. However, by combining PMCT results with detailed knowledge of the circumstances of death, the diagnosis is likely to be correct in up to 60 % [13, 14]. In clinical practice, cardiac MDCT including contrast-enhanced CT coronary angiography is fast emerging as a powerful diagnostic tool for the assessment of coronary disease in both acute and chronic cases [59–61].

If minimally invasive autopsy using PMCT is to be implemented for routine coronial autopsies, the numbers of cadavers to be examined will run into thousands

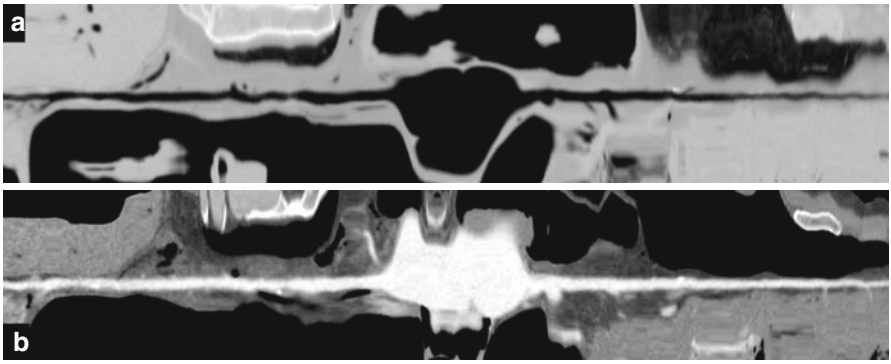

Fig. 1.11 Targeted coronary PMCTA with air (**a**) and water-soluble contrast agent (**b**) showing mildly diseased right and left coronary arteries reconstructed using straightened curved MPR (cMPR) (Images courtesy of Morgan B & Rutty G, University of Leicester, UK)

and complex approaches, such as whole body multiphase PMCTA techniques as described previously, may be impractical. Independently two centers in the UK decided to augment PMCT by direct contrast injection into the ascending aorta and therefore the coronary arteries. In both cases the objective was to provide a straightforward method of investigating for coronary artery disease that was quick, cost-effective and easy to perform [62, 63]. Both techniques describe cut down into the left carotid artery and direct insertion of a catheter of the type used for bladder catheterization. The catheter balloon is then inflated in the ascending aorta so contrast can be injected into the aortic root. Backflow occurs into the left ventricle but is resisted by the aortic valve and the compliance of the ventricle muscle and mitral valve. This allows filling of the coronary arteries.

Both techniques use standard clinical water-soluble contrast agents dissolved in water rendering them hypo-osmolar. They have not observed the same problems with widespread tissue edema affecting post procedure histological analysis [64], but the quantity of agent used is less than for whole body techniques and the concentration of iodine (mgI/ml) used is also less.

The techniques differ in their approach. The technique developed in Oxford uses only positive contrast media and makes efforts to avoid air within the vessels [63]. The system developed in Leicester, however, deliberately uses both air and contrast media (Figs. 1.2b, 1.3a, and 1.11). Another difference of the two techniques, and a potential advantage of this approach, is the use of standard clinical CT power contrast injectors to image the coronary vessels dynamically during contrast injection, which has the potential to mimic physiological pressure and provide a more meaningful assessment of vessel stenosis [64, 65]. The technique involves accessing the left carotid artery in the mortuary by cut down using a modified 14Ch Foley urinary catheter inserted by the study technician [62]. In the CT scanner the position of the Foley catheter in the ascending aorta is confirmed and the (large) balloon is inflated. A standard clinical pump injector is then used to inject 300 ml air at 6 ml/s, two times supine and then once in the right lateral decubitus position. Contrast

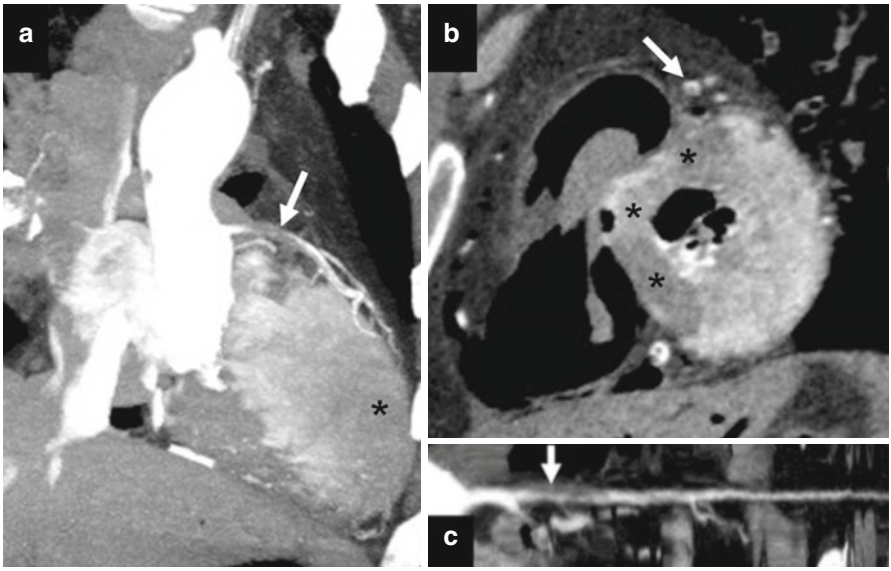

Fig. 1.12 Targeted coronary PMCTA using water-soluble contrast agent: (**a**, **c**) shows a mixed plaque occluding the left anterior descending artery (*arrows*) and (**b**) an associated perfusion deficit in the anterior septal myocardial wall (*). This sign is helpful but not specific to infarction as perfusion deficits may be seen in normal myocardium (Images courtesy of Morgan B & Rutty G, University of Leicester, UK)

(Urografin® 150 mg/ml; Bayer Healthcare, positive contrast) diluted 1:10 is then injected, first in the right lateral decubitus position and then supine. Imaging is performed to run concurrent with the end of the injection so images are acquired while the arteries are under pressure [65].

Studies comparing these techniques with autopsy show that they perform well in identifying significant ischemic heart disease (Fig. 1.12) [63, 66], and they also correlate well with detailed microscopic and histological investigations of the vessels [64]. This is in agreement with whole body approaches [47]. In fact by investigating the vessels under pressure, this technique may outperform pathology, where heavily calcified vessels may appear stenotic to the pathologist due to the trauma of sectioning the vessel for pathology assessment (Fig. 1.13) [64]. A further advantage of the localized targeted approach is that there is no significant effect on biochemical and toxicological analysis performed post procedure [67].

One issue relating to all PMCTA techniques is that in clinical cardiac angiography and CT cardiac angiography, qualitative assessment of stenosis does not necessarily correlate with clinical significance [68, 69]. It is therefore debatable that critical coronary artery stenosis alone, diagnosed by PMCTA, can be used to diagnose cause of death. However, there is evidence that severe coronary artery disease does predict for coronary occlusion [70] and even at autopsy it can be very difficult to be certain of the cause of sudden death, unless there is a clear occlusive thrombus. For this reason the cause of death is more commonly attributed to "ischemic heart

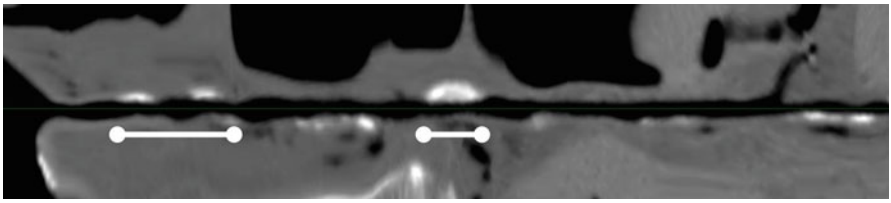

Fig. 1.13 Targeted coronary PMCTA with air showing a diseased coronary artery reconstructed using straightened curved MPR (cMPR). The areas denoted by a white line were reported as critical (>75 %) stenosis on pathological examination but are more patent after distension by air (Images courtesy of Morgan B & Rutty G, University of Leicester, UK)

disease" on the "*balance of probabilities*" rather than specifically to cardiac occlusion, if no other cause of death is ascertained [58]. In fact, in sudden death from cardiac occlusion, myocardial infarction cannot be diagnosed with absolute certainty at autopsy if death is caused by immediate causes such as arrhythmia, and similarly the presence of thrombus is not proof of "cause and effect" as thrombus has been seen in cases of noncardiac death [71].

For any investigation if the initial test gives no answer, then further testing would be performed. However, an important caveat in the use of PMCT and PMCTA, and even for autopsy, is that if two potentially lethal pathologies are present and only one is demonstrated, such as a critically stenosed coronary artery, then this may be given as the single cause of death "*on the balance of probabilities*," and the real cause of death may be missed. For PMCTA fatal pulmonary thromboembolism could be missed and therefore misdiagnosed in the presence of severe unrelated coronary artery disease. However, PMCTA, in combination with the correct clinical situation, a thorough external examination and toxicology if necessary, is unlikely to miss unnatural death.

Conclusion

These three methods provide distinct ways of providing vascular and, to a lesser extent, parenchymal contrast enhancement information to postmortem CT. All methods could be adopted in any unit providing forensic services, even when using hospital clinical scanners. The choice of method will rest on several factors, including cost, local experience, time available on the scanner, and local cultural and religious preferences. Ideally, however, the choice will also rest on using the most suitable method for the individual case. As can be seen from the development of these methods, modifications are possible to the choice of contrast media that would change the information achieved and therefore would allow each method to be further refined for the individual case. The authors have no doubt that the use of these contrast-enhanced methods will further strengthen the role of PMCT in forensic investigation.

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