The Lausanne forensic pathology approach to post-mortem imaging for natural and non-natural deaths

Virginie Magnin
Silke Grabherr
Katarzyna Michaud

Abstract

Post-mortem imaging by computed tomography (PMCT) and post-mortem CT angiography (PMCTA) are used routinely in forensic practice as components to the autopsy. PMCT is efficient for gas detection, foreign body visualization and skeleton analysis. Various parameters can lead to the indication for contrast agent injection. Contrast injection into the vascular system can overcome the disadvantages of non-contrast PMCT by visualization of solid organ parenchyma and vessels. This can also assist the conventional autopsy, allowing one to investigate the vascular system. It is the method of choice for the analysis of the blood vessels by showing vascular pathology, congenital or postsurgical anatomical variations and an exact source of bleeding. By knowing the artefacts linked to the angiographic technique, we limit the risk of misinterpretation. The use of post-mortem MRI (PMMR) for diagnostic purposes is still limited to rare indications. These include review of the neck in cases of death by mechanical asphyxia, total-body PMMR in neonatal and pediatric death and cardiac PMMR in case of suspected myocardial infraction. Currently, in our daily practice, the vast majority or PMMR is only performed for research purposes.

Keywords autopsy; computed tomography; PMCT; PMCTA; PMMR; post-mortem imaging

Virginie Magnin *MD Centre Universitaire Romand de médecine légale (CURML), Lausanne, Switzerland and University Hospital of Lausanne, University of Lausanne. Conflicts of interest: none declared.*

Silke Grabherr *MD Centre Universitaire Romand de médecine légale (CURML), Lausanne, Switzerland and University Hospital of Lausanne, University of Lausanne. Conflicts of interest: none declared.*

Katarzyna Michaud *MD Centre Universitaire Romand de médecine légale (CURML), Lausanne, Switzerland and University Hospital of Lausanne, University of Lausanne. Conflicts of interest: none declared.*

The role of radiological imaging in autopsy practice

An introduction to post-mortem computed tomography (PMCT)

PMCT has become an important adjunct for conventional autopsy having both advantages and disadvantages. In the University Center of Legal Medicine, Lausanne-Geneva (Centre Universitaire Romand de Médecine Légale, CURML), over the last 10 years, all cases have had whole-body (head to toe) post-mortem computed tomography (PMCT), actually on our 64-row CT VCT LightSpeed 8, GE Healthcare unit. These investigations, regardless of whether the medico-legal investigations, require an external examination or an autopsy. The main interests for the use of PMCT are trauma cases, requiring review of the skeletal system as in cases of a fall from height, blunt force trauma or traffic accident. Other indications are ballistic trauma, child abuse, detection of foreign bodies and identification.

Regardless of the case, the interpretation of the PMCT commences with the initial 'scout view'. This image allows ready detection of foreign bodies of medico-legal interest such as projectiles or the presence of medical devices (Figure 1). The latter are important for identification purposes, especially in decomposed bodies. PMCT also provides information on the presence of fractures and can provide a rapid overlook of potential traumatic injuries. Then, following detailed analysis of the PMCT, it is possible to establish a detailed map of fractures, to localize precisely radiopaque foreign material, or to detect foci of hemorrhage (hemothorax, hemoperitoneum, intracerebral hemorrhage), any and all of which may be indicative of exsanguination or traumatic damage to internal organs. Thanks to the very low X-ray attenuation of gas, its presence in the body cavities (pneumothorax, pneumoperitoneum), can easily be detected. This is a big advantage compared to conventional autopsy, where gas can easily escape the forensic pathologist recognition when opening the body cavities. Depending on its distribution,- the presence of the gas can even inform the pathologist about an intracorporeal trajectory of a gunshot trauma or sharp trauma for example. PMCT will also help to depict skeletal injury or malformation in cases of infant death, which may be difficult to see at conventional autopsy.

In cases where the exact cause of death is demanded by the prosecutor, a medico-legal autopsy will be ordered following PMCT. Prior to the opening of the body cavities, it is important to decide if a post-mortem angiography would assist. The injection of contrast agent into the vascular system can overcome, not only the disadvantages of standard PMCT but also those of the conventional autopsy. The opportunity to fully investigate the vascular system may be of great help in most cases. Therefore, the reported circumstances of the case, medical history of the deceased and the analysis of the native PMCT can lead to the indication of a post-mortem angiography.

In the CURML, a standardized protocol of angiography involves the multi-phase post-mortem CT angiography (MPMCTA) that was developed in our centre.[1] It is, however, recommended to take blood samples for toxicological and microbiological analysis before the injection of any contrast agent.[2,3]

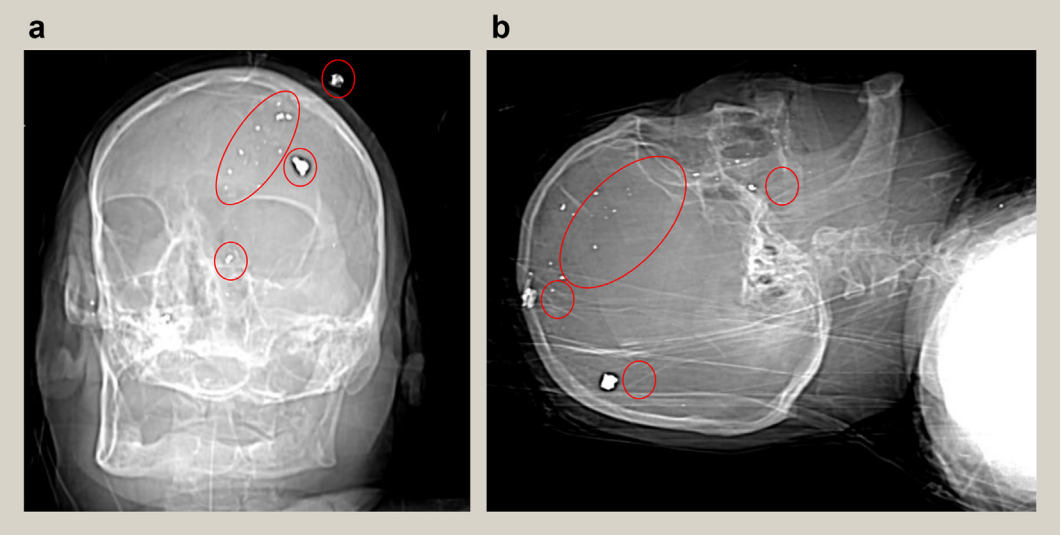

Figure 1 Scout views (**a, b**) of the PMCT. Foreign material (projectile) in a case of transcranial gunshot wound (red circles).

The technique of MPMCTA and its indications

The standardized technique of MPMCTA includes the performance of multiple image acquisitions on the body during and after the perfusion of the vascular system. According to the protocol, prior to any angiographic manipulation of the body, a standard PMCT has to be performed. Those images are not only important for indicating the need of the contrast agent injection, but also to provide some control image data that can be used for those images acquired after the perfusion of the body.

Once the PMCT is performed, the body can be prepared for the injection of contrast agent, meaning samples for toxicological, biochemical, bacteriological and other specific analysis have to be taken by biopsies or needle-puncture. MPMCTA starts with the femoral artery and vein of one side of the body being freed from the surrounding tissue, thus allowing the insertion of cannulas which shall be connected to the tubing system.

The perfusion device used in our center is a Virtangio® perfusion machine (FUMEDICA AG, Muri bei Bern) which infuses a contrast agent mixture into the cannulated femoral artery and vein. This device is somewhat similar to a bypass pump. Different contrast agents exist. In our center, we mainly inject a mixture of Paraffin oil (Paraffinum Liquidum from local pharmacies) and Angiofil® (FUMEDICA AG, Muri bei Bern) at 6 %. Then, following the standardized protocol, 1200 ml of the contrast-agent mixture is introduced with a flow rate of 800 ml/min. Once the volume is injected, the perfusion is stopped (automatically by using the Virtangio® device) and an image acquisition is done, the so-called “Arterial Phase”.

The same procedure is repeated for obtaining the “Veinous Phase” for which 1800 ml are injected using the same flow rate. Finally, a last angiographic phase is obtained by performing a data acquisition during an ongoing perfusion (injection of 500 ml into the artery with a flow rate of 200 ml/min).[1] Our experience has shown that by comparing the different images obtained during the different phases of MPMCTA, reliable diagnostic analyses can be made.[4]

Progression to MPMCTA depends firstly on the results of the non-contrast PMCT and also on the suspected cause of death (according to medical history of the case and circumstances of the death). In our centre the rule is to first utilize a MPMCTA in cases where vascular lesions are suspected. The final decision whether an MPMCTA can be done, or not, is made by the prosecutor in charge of the case. Knowing that with conventional autopsy, visualization of vessels is difficult, or sometimes impossible especially if they are small, MPMCTA is the method of choice for the analysis of the vascular system.

It can demonstrate vascular pathology such as dissection (Figure 2), aneurysm, congenital vascular anatomical variants or anatomical variations being the consequence of a surgical intervention such as a graft or a bypass. Most importantly, it can detect an exact source of bleeding (Figure 3). In cases where a natural cause of death is suspected, the presence on the non-contrast PMCT of a subarachnoid hemorrhage without history of trauma, of a cerebral intra-parenchymal hemorrhage, of a zone of cerebral softening or of an intra-cranial mass are indications for utilizing contrast media in order to detect the presence of a ruptured aneurysm, an arteriovenous malformation, a carotid artery or circle of Willis occlusion or a tumor.

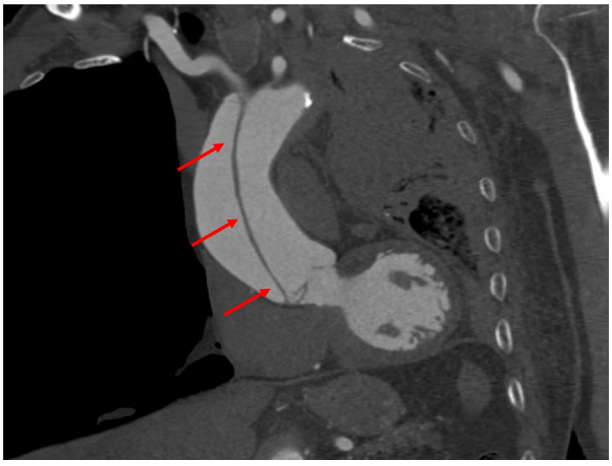

Figure 2 MPMCTA, arterial phase: ascending aortic dissection (red arrows).

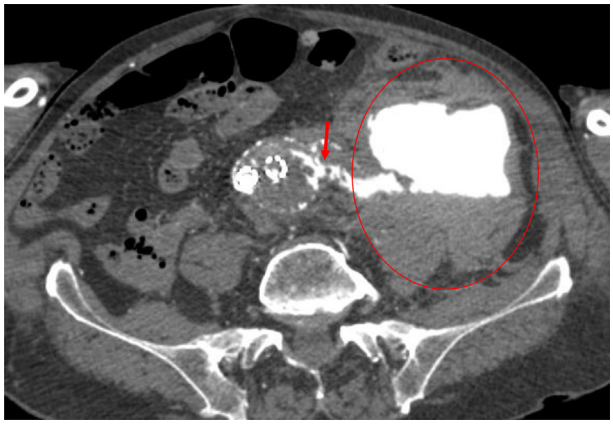

Figure 3 MPMCTA, arterial phase: MPMCTA showing the localization of the source of bleeding from an endoprothesis of the abdominal aorta (red arrow) with leakage of contrast agent in the peritoneum (red circle).

The discovery of a hemopericardium or hemoperitoneum will prompt MPMCTA in order to examine the extension of an aortic dissection, a ruptured abdominal aortic aneurysm or a hemorrhagic lesion of an abdominal organ. In cases of suspected cardiovascular death, the presence of coronary calcification or calcification of the myocardium, may indicate an old infarction and suggest the use of the contrast injection to localize a potential coronary thrombosis. Once located on the radiological images, the image data can guide sampling for histological confirmation during open autopsy.

In the event of intraoperative or immediate postoperative death, the injection of contrast medium is recommended because it will demonstrate hemorrhagic complications. These are well known in cardiovascular surgery, after a valve replacement or coronary artery bypass surgery. In abdominal surgery or after hepatic or renal percutaneous biopsy, bleeding sources can also be readily detected with MPMCTA. Postsurgical complications such as accidental vessel damage can also be highlighted.[5] Other complications such as suture dehiscence or malposition of implants can be detected at the non-contrast PMCT, and therefore injection of contrast medium is not mandatory. However, MPMCTA could provide additional information, especially when considering intravascular implants. In the cases of trauma by firearm or sharp trauma, the trajectory of the projectile or of the blade is usually highlighted by the leakage of contrast agent, which will be visible in soft tissues and organs[6] (Figure 4).

Limits of the PMCT and MPMCTA and their artefacts

Non-contrast or plain PMCT is efficient for gas detection, but in case of suspicion of gas embolism, the CT-guided sampling of cardiac gas is essential. As demonstrated by certain studies, the development of post-mortem gas can be misinterpreted as ante mortem gas embolism, as this process begins within hours following death.[7]

The knowledge of usual post-mortem gas distribution is required to avoid misinterpretation, especially in putrefied bodies where the post-mortem radiological alteration index should be used.[7] As with CT scans in living patients, standard PMCT is somewhat poor in the analysis of solid organs parenchyma and vascular system. For this reason, MPMCTA plays an important role.

MPMCTA also has its limits. In order to interpret correctly the obtained images, it is important to know technique-related artefacts. For MPMCTA, these are appreciated and can be grouped in three different categories: those related to the perfusion method, those related to post-mortem changes and iatrogenic artefacts.[8] All these artefacts must be well recognized and understood in order to avoid misinterpretation/s. Contrast layering, filling defects and incomplete perfusion of head and neck vessels are artefacts related to the perfusion method. Contrast layering is easy to recognize as a line between the dense contrast on the top

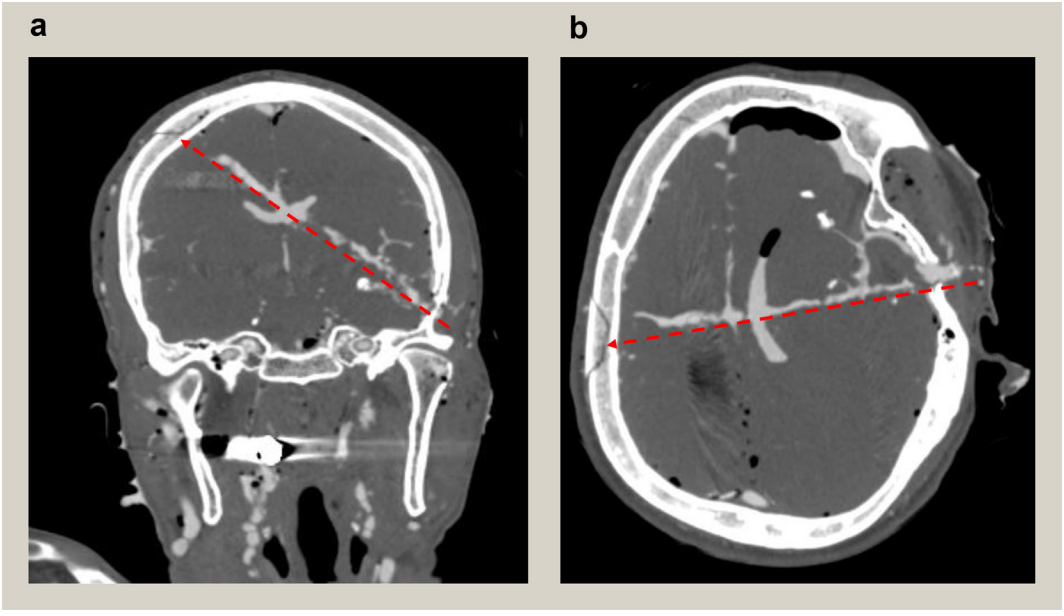

Figure 4 Coronal (**a**) and axial (**b**) views of the MPMCTA, arterial phase: trajectory of the projectile demonstrated by the leakage of contrast agent through the brain parenchyma (red dashed arrow).

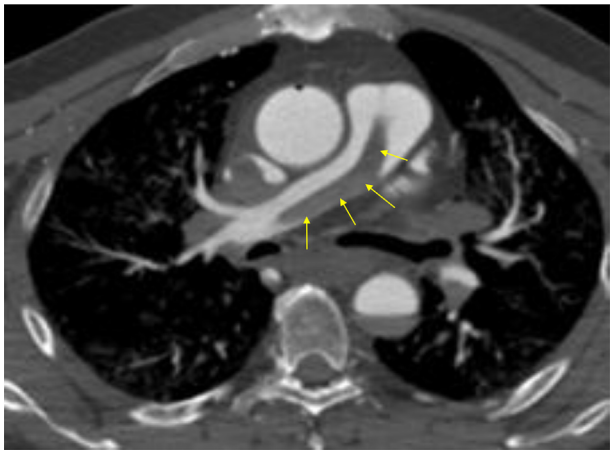

Figure 5 Axial view of the MPMCTA, arterial phase: artefact related to perfusion method. Filling defect is seen in the pulmonary trunk and right pulmonary artery (yellow arrows) mimicking a pulmonary embolism.

and the hypodense blood on the bottom of the vessel lumen. This can be explained by the fact that the oily contrast agent used for the MPMCTA does not mix with the residual blood, giving an appearance of two different layers. More difficult to analyze are the filling defect artefacts, as they can reflect a real occlusion or stenosis of a vessel, but may also be due to the presence of post-mortem clots in the vascular system.

If a filling defect remains identical from a morphological and geographical point of view at the three different phases of injection, a stenosis or occlusion due to a real pathological finding is likely. This has still to be correlated to the autopsy finding in order to identify its exact nature. One artefact often encountered, related to the perfusion method is the filling defect in the pulmonary trunk or arteries, which can mimic a pulmonary embolism[2,9] (Figure 5).

The artefacts related to post-mortem changes are mainly visible in the form of leakage of contrast medium. They are due to the post-mortem autolysis of organs. They are regularly seen in organs with high enzymatic activity such as the pancreas, the mucosa of the gastrointestinal tract and the right renal vein because of its localization close to the head of the pancreas.

The iatrogenic artefacts are either secondary due to sample collection (extravasation of contrast agent along the path of the inserted needle) or to the manipulation of the body. In putrefied (decomposing) bodies, two additional artefacts can be encountered. These are enhancement of the adrenal glands due to contrast agent accumulation and leakage of contrast agent in the orbits visible during the venous phase.[2]

Post-mortem MRI (PMMR)

PMMR can be a valuable tool to document pathological or forensic findings.[10,11] PMMR, because of its better contrast for the soft tissues can provide more detailed information than PMCT and can highlight conditions which would not have been shown with PMCT, such as ischemic myocardium or cervical spine injury.[11] Although MRI is the only imaging modality that can visualize soft tissue and organs in a manner similarly to autopsy, in our current practice, indications for PMMR for diagnostic purposes are still limited, because of the difficulty of its interpretation.

Indeed, even today, a lack of studies concerning the correlation between images and histology, especially immunohistochemistry, exists. Therefore, the limitations of the methods remain somewhat unclear. In addition, its performance is much more complicated from a technical and practical point of view.

Due to a long examination time, PMMR is mostly only performed in one anatomic region of specific interest and costs are relatively high. Therefore, it cannot be used as a screening method like standard PMCT.[12] As in T2 weighted images, liquid elements appear white, it is easy to recognize areas of fluid accumulation as in the case of subcutaneous hematoma, bone contusion and pleural or pericardial effusion for example.

In the event of a strong suspicion of death of cardiac origin, in a young patient or in the absence of coronary calcifications at PMCT, we usually perform an unenhanced cardiac PMMR on our Philips 1,5 Tesla Ingenia CX device. Unlike in clinical radiology, where contrast enhancing agent injection is used, we do not have the possibility to assess the late enhancement used to diagnose ischemic lesions in PMMR. This is due to the fact that, after death, there is no more cellular activity. However, in return we are spared cardiac and respiratory motion artefacts, allowing an excellent image quality. Currently, in our daily practice, the vast majority of MRI exams performed in our center are for research purposes.

The diagnostic approach

Radiological examination of cardiovascular diseases

Cardiovascular diseases represent the most frequent causes of natural deaths in western countries, especially in elderly patients. The most frequent is ischemic heart disease and especially myocardial infarction. In younger patients, the cardiomyopathies and channelopathies are more often observed, although myocardial infarctions are also reported. Post-mortem radiological examination of the cardiovascular system is limited to the morphological evaluation of the heart and vessels as it is evidently impossible to perform functional assessment. On the other hand, movement artefacts being well known in living patients related to respiration and heart movements, are not a problem in post-mortem approach. The radiological examination allows documentation of the heart and vessels before the dissection.

Examination by PMCT gives the first idea about the heart size, coronary calcifications and presence of a haemopericardium. The increased heart size, described radiologically as cardiomegaly suggests that the heart is pathological and in particular that some cardiomyopathies, advanced ischemic heart disease or valvular diseases could be present. The heart size is estimated radiologically first by the measurement of the cardiothoracic ratio (CTR). The post-mortem CTR is influenced by body mass index and the heart dilatation that could be related to perimortem phenomena.[13] It cannot be used alone to discriminate between normal heart weight and overweight heart. A new formula of adjusted CTR based score proposed by Jotterand et al. helps to predict "cardiomegaly" at PMCT.[14] Several studies have shown that various cardiac measurements of valves, wall thicknesses etc. differ from corresponding autopsy measurements.[15–18] The exceptions are aorta measurements, that correlate with measurements obtained at autopsy with PMCTA.[17] PMMR is considered as the method of choice for the radiological investigation of the myocardium.

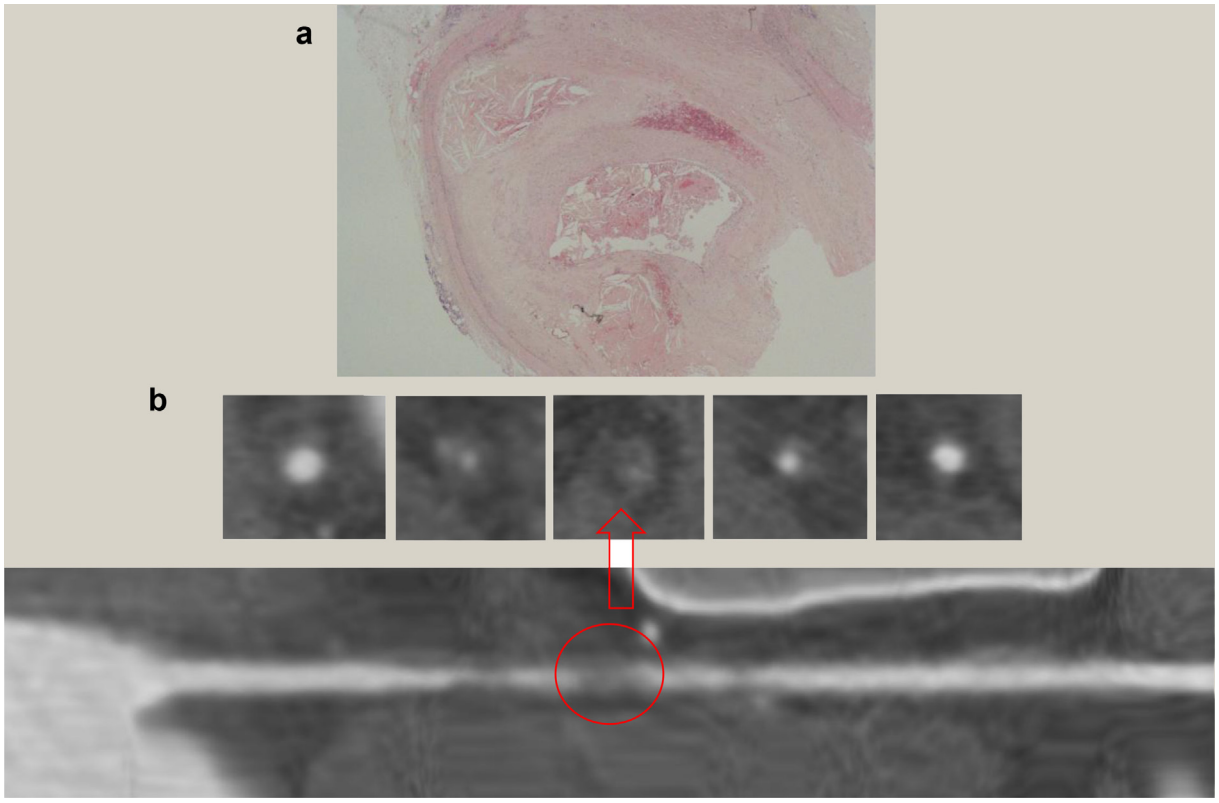

Figure 6 Histologic slide (**a**) and MPMCTA angiographic view (**b**) of the right coronary artery: subocclusion of the medial part of the right coronary artery with histologic correlation.

Evaluation of coronary arteries is one of the essential steps in post-mortem examination. Coronary calcifications are easily detectable and quantifiable in PMCT. Clinical calcium scoring is considered to be a marker of a vascular pathology that correlates closely with overall atherosclerotic burden and allows to predict the clinical risks for living patients. In post-mortem examination, it is known that some thrombosed coronaries are not calcified, or show calcifications which could be clinically considered as minimal or moderate.[19,20] An acute occlusion or a severe chronic coronary artery disease may explain the death and therefore the examination of the lumen is very important. The perfusion of coronary arteries can be assessed radiologically only by using a contrast as in PMCTA or PMMRA[4,21] (Figure 6).

Malformations of vessels (malposition of the coronary arteries, transposition or stenosis of the great vessels) are partially visible in the PMCT but can be well appreciated in the PMCTA and the PMMR. The radiological methods by PMCT, PMCTA and PMMR can be helpful in neonatal and fetal cases.[22,23]

Death after cardiovascular interventions can be related to post-operative hemorrhage. PMCT is particularly useful in detecting the exact localization of foreign bodies, such as surgical material, coronary stents, clips and prostheses. PMCTA allows visualization and documentation of a source of bleeding, allows the pathologist to check the perfusion of coronary bypass grafts and to verify the correct position and the function of any vascular prosthesis. The autopsy technique can then be adapted, according to the radiological evaluation.[23–25]

It is well known that post-mortem imaging methods are still less accurate than the reference standard for soft tissues and organ findings observed in natural deaths. The pooled sensitivity for the correct cause of death is the highest for PMCTA followed by PMCT/PMMR.[4,26–28] There remain controversies about the diagnostic value of post-mortem imaging for the detection of myocardial infarction, although some investigators suggest that post-mortem imaging and especially minimal invasive autopsy can even replace the standard autopsy in cases of a suspected myocardial infarction and that the combination of PMMR with heart biopsies had high sensitivity and specificity for the detection of myocardial infarction.[4,25,26,29,30]

It is generally admitted that unenhanced PMCT may have a limited diagnostic value. Angiographic post-mortem methods enable evaluation of coronary artery lumen, detecting stenosis and suspected occlusions.[24,31] As suggested in different studies unenhanced PMMR can be used to assess for the presence of myocardial ischemia, based on a morphological visualization of the investigated structures.[11,29,30,32]

Jackowski et al. suggested that it is possible to discriminate the age of the myocardial lesion with the use of a 1,5 T system where acute ischemia showed two different areas of signal behavior, a signal reduction within the necrotic center of the myocardial wall in T2-weighted images with increased signal in subepicardial marginal regions.[33] Subacute ischemia showed increased signal in T2 weighted images and chronic ischemia showed decreased signal in all sequences, especially in T2

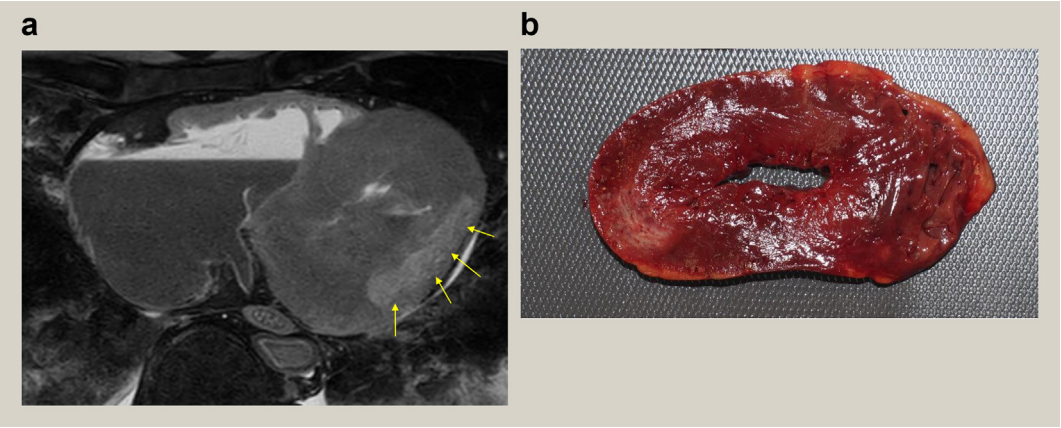

Figure 7 PMMR T2 DIXON (**a**) and macroscopic slide of the heart (**b**). Myocardial infarction of the lateral wall of the left ventricle visible as an increased signal on T2 DIXON sequence (yellow arrows) corresponding to an acute and old myocardial infarction at autopsy.

weighted images and were also reported on a 3T MRI[33] (Figure 7).

Furthermore, MPMCTA has been suggested to be able to detect infarcted areas as regions of pathological enhancement, helping to identify affected regions. We consider that further studies are needed to establish the diagnostic value of this method.[34,35] As explained above, radiological methods do not enable the certain differentiation between vital thrombus and post-mortem clot. In addition, they cannot identify exactly the origin of a vascular occlusion. Post-mortem MPMCTA does not permit the diagnosis of specific myocardial pathologies such as myocarditis or cardiomyopathies.

Other non-cardiac chest disease diagnoses

Pulmonary diagnosis is perceived to be difficult in most cases. The lung shows great variety of imaging alteration in PMCT that can be related to hypostasis (livor mortis). They can easily be mistaken as aspiration, pulmonary edema or pneumonia.[36,37] Moreover, it is known that the presence of lung imaging alteration in PMCT does not mean that the lung was involved in any process of forensic relevance, as the lungs show many unspecific findings that appear in perimortem events, independent of the cause of death.[36]

Common major errors on thoracic imaging, reported already in 2010, are missed diagnoses of pulmonary thromboembolism and pneumonia.[38] It was suggested that unenhanced PMMR could demonstrate pulmonary thromboembolism in situ. However, special attention has to be drawn to the differentiation of post-mortem clots.[39]

Fat embolism (FE) to the pulmonary arteries is caused mainly by bone fractures in traumatic deaths, but can be observed also in some non-traumatic deaths as pancreatitis, fatty liver and sickle cell disease. The autopsy detection of this pathology is difficult and special techniques are necessary. In post-mortem imaging, a "fat-fluid level" in the right heart or intraluminal fat in the pulmonary arterial branches can suggest FE in cases with a massive FE (Falzi grade III). This is more easily detectable in PMMR than in PMCT.[40] The use of MPMCTA is limited as the oily contrast agent mixture mimics FE.[12] In such cases, pre-angiography pulmonary biopsies are suggested or the change of the applied contrast agent.

Pneumothorax can be diagnosed more easily at PMCT than at autopsy. However, special attention should be taken in putrefied bodies where interpreting the presence of gas and the post-mortem alteration index could be helpful.[8] Depending on the case, the gas detected in PMCT could be sampled for toxicological analyses in order to verify its composition and therefore to understand its origin.

Neonatal and pediatric imaging

Due to its high tissue contrast and its ability to visualize soft-tissue infiltration, PMMR is the modality of choice in post-mortem neonatal and pediatric imaging. In our center, a total body MRI is systematically performed to investigate sudden death in infants. In those cases, it allows to detect small soft tissues infiltrations or subtle acute fractures which are visible due to the associated bone marrow edema.

Non-natural deaths

MPMCTA is the method of choice for the evaluation of vascular lesions caused in situations often encountered in forensic medicine; such as blunt force trauma (traffic accident, fall from a great high), sharp trauma and gunshot trauma. In thoracic blunt trauma for example, MPMCTA will allow the visualization of injured intercostal arteries in case of displaced costal fracture with hemothorax. The precise location of a cardiac laceration with leakage of contrast medium or of a tear in the thoracic aorta will often be well visualized.

In order to see lesions of solid abdominal organs, contrast-agent injection is mandatory as it will permit the detection of intraparenchymal lacerations, capsular laceration with leakage of contrast medium in the peritoneum, sub capsular hematoma and traumatic abdominal aortic dissection. Vascular lesions secondary to complex pelvic fractures, which proved to be rapidly fatal, will be diagnosed by MPMCTA due to the leakage of contrast.

In sharp and gunshot trauma, MPMCTA will not only facilitate identification of the vital structures affected, but also helps to evaluate the intracorporeal trajectory of the projectile or a blade. In our center, an MRI of the neck is systematically carried out with T1-and T2-weighted sequences, in cases of death by mechanical asphyxia (strangulation or hanging). In those cases, the

examination allows one to highlight possible infiltration of soft tissue and/or the presence of intramuscular hemorrhage. ◆

Practice points

- Post-mortem imaging is useful as a complementary tool for natural and violent deaths
- Possible artefacts should be considered while interpreting post-mortem radiological images
- Post-mortem imaging methods are less accurate than the autopsy for cardiac deaths

REFERENCES

1 Grabherr S, Doenz F, Steger B, et al. Multi-phase post-mortem CT angiography: development of a standardized protocol. *Int J Leg Med* 2011; **125:** 791–802.
2 Grabherr S, Grimm JM, Heinemann A. Atlas of post-mortem angiography, 2016.
3 Palmiere C, Grabherr S, Augsburger M. Post-mortem computed tomography angiography, contrast medium administration and toxicological analyses in urine. *Leg Med* 2015; **17:** 157–62.
4 Grabherr S, Heinemann A, Vogel H, et al. Post-mortem CT angiography compared with autopsy: a forensic multicenter study. *Radiology* 2018; **288:** 270–6.
5 Heinemann A HV. Post-mortem angiography after invasive surgery. In: Grabherr S, Grimm JM, Heinemann A, eds. Atlas of post-mortem angiography. Sringer International Publishing, 2016.
6 Ruder TD, Ross S, Preiss U, Thali MJ. Minimally invasive post-mortem CT-angiography in a case involving a gunshot wound. *Leg Med* 2010; **12:** 154–6.
7 Egger C, Bize P, Vaucher P, et al. Distribution of artifactual gas on post-mortem multidetector computed tomography (MDCT). *Int J Leg Med* 2012; **126:** 3–12.
8 Egger C, Vaucher P, Doenz F, Palmiere C, Mangin P, Grabherr S. Development and validation of a post-mortem radiological alteration index: the RA-Index. *Int J Leg Med* 2012; **126:** 559–66.
9 Bruguier C, Mosimann PJ, Vaucher P, et al. Multi-phase post-mortem CT angiography: recognizing technique-related artefacts and pitfalls. *Int J Leg Med* 2013; **127:** 639–52.
10 Thali MJ, Yen K, Schweitzer W, et al. Virtopsy, a new imaging horizon in forensic pathology: virtual autopsy by post-mortem multislice computed tomography (MSCT) and magnetic resonance imaging (MRI)–a feasibility study. *J Forensic Sci* 2003; **48:** 86–403.
11 Ruder TD, Thali MJ, Hatch GM. Essentials of forensic post-mortem MR imaging in adults. *The Br J Radiol* 2014; **87:** 20130567.
12 Grabherr S, Egger C, Vilarino R, Campana L, Jotterand M, Dedouit F. Modern post-mortem imaging: an update on recent developments. *Forensic Sci Res* 2017; **2:** 52–64.
13 Jotterand M, Doenz F, Grabherr S, et al. The cardiothoracic ratio on post-mortem computer tomography. *Int J Leg Med* 2016; **130:** 1309–13.
14 Jotterand M, Faouzi M, Dedouit F, Michaud K. New formula for cardiothoracic ratio for the diagnosis of cardiomegaly on post-mortem CT. *Int J Leg Med* 2020; **134:** 663–7.
15 Ampanozi G, Hatch GM, Flach PM, Thali MJ, Ruder TD. Post-mortem magnetic resonance imaging: reproducing typical autopsy heart measurements. *Leg Med* 2015; **17:** 493–8.
16 Chatzaraki V, Thali MJ, Schweitzer W, Ampanozi G. Left myocardial wall measurements on post-mortem imaging compared to autopsy. *Cardiovasc pathol : off j Soc Cardiovasc Pathol* 2019; **43:** 107149.
17 Troxler R, Minoiu C, Vaucher P, et al. The role of angiography in the congruence of cardiovascular measurements between autopsy and post-mortem imaging. *Int J Leg Med* 2018; **132:** 249–62.
18 Jakobsen LS, Lundemose S, Banner J, Lynnerup N, Jacobsen C. Forensic post-mortem computed tomography: volumetric measurement of the heart and liver. *Forensic Sci Med Pathol* 2016; **12:** 510–6.
19 Michaud K, Grabherr S, Doenz F, Mangin P. Evaluation of post-mortem MDCT and MDCT-angiography for the investigation of sudden cardiac death related to atherosclerotic coronary artery disease. *The int j cardiovasc Imag* 2012; **28:** 1807–22.
20 Michaud K, Grabherr S, Faouzi M, Grimm J, Doenz F, Mangin P. Pathomorphological and CT-angiographical characteristics of coronary atherosclerotic plaques in cases of sudden cardiac death. *Int J Leg Med* 2015; **129:** 1067–77.
21 Grabherr S, Grimm J, Baumann P, Mangin P. Application of contrast media in post-mortem imaging (CT and MRI). *Radiol Med* 2015; **120:** 824–34.
22 Michaud K, Grabherr S, Jackowski C, Bollmann MD, Doenz F, Mangin P. Post-mortem imaging of sudden cardiac death. *Int J Leg Med* 2014; **128:** 127–37.
23 Michaud K, Genet P, Sabatasso S, Grabherr S. Post-mortem imaging as a complementary tool for the investigation of cardiac death. *Forensic Sci Res* 2019; **4:** 211–22.
24 Morgan B, Biggs MJ, Barber J, et al. Accuracy of targeted post-mortem computed tomography coronary angiography compared to assessment of serial histological sections. *Int J Leg Med* 2013; **127:** 809–17.
25 Michaud K, Basso C, d'Amati G, et al. Diagnosis of myocardial infarction at autopsy: AECVP reappraisal in the light of the current clinical classification. *Virchows Arch* 2020; **476**(2)**:** 179–94.
26 Blokker BM, Wagensveld IM, Weustink AC, Oosterhuis JW, Hunink MG. Non-invasive or minimally invasive autopsy compared to conventional autopsy of suspected natural deaths in adults: a systematic review. *Eur radiol* 2016; **26:** 1159–79.
27 Ampanozi G, Halbheer D, Ebert LC, Thali MJ, Held U. Post-mortem imaging findings and cause of death determination compared with autopsy: a systematic review of diagnostic test accuracy and meta-analysis. *Int J Leg Med* 2020; **134**(1)**:** 321–37.
28 de Boer HH, Dedouit F, Chappex N, van der Wal AC, Michaud K. Sudden aortic death-proposal for a comprehensive diagnostic approach in forensic and in clinical pathology practice. *Int J Leg Med* 2017; **131:** 1565–72.
29 Rutty GN, Johnson C, Amoroso J, Robinson C, Bradley CJ, Morgan B. Post-mortem computed tomography coaxial cutting needle biopsy to facilitate the detection of bacterioplankton using PCR probes as a diagnostic indicator for drowning. *Int J Leg Med* 2017; **131:** 211–6.
30 Wagensveld IM, Blokker BM, Pezzato A, et al. Diagnostic accuracy of post-mortem computed tomography, magnetic resonance imaging, and computed tomography-guided

biopsies for the detection of ischaemic heart disease in a hospital setting. *Eur Heart J Cardiovasc Imag* 2018; **19:** 739–48.

31 Roberts ISD, Traill ZC. Minimally invasive autopsy employing post-mortem CT and targeted coronary angiography: evaluation of its application to a routine Coronial service. *Histopathology* 2014; **64:** 211–7.

32 Jackowski C, Warntjes M, Berge J, Bär W, Persson A. Magnetic resonance imaging goes post-mortem: noninvasive detection and assessment of myocardial infarction by post-mortem MRI. *Eur radiol* 2011; **21:** 70–8.

33 Jackowski C, Schwendener N, Grabherr S, Persson A. Post-mortem cardiac 3-T magnetic resonance imaging: visualization of sudden cardiac death? *J Am Coll Cardiol* 2013; **62:** 617–29.

34 Sabatasso S, Vanhaebost J, Doenz F, et al. Visualization of myocardial infarction in post-mortem multiphase computed tomography angiography: a feasibility study. *The Am j forensic med pathol* 2018; **39:** 106–13.

35 Vanhaebost J, Faouzi M, Mangin P, Michaud K. New reference tables and user-friendly Internet application for predicted heart weights. *Int J Leg Med* 2014; **128:** 615–20.

36 Filograna L, Thali MJ. Post-mortem CT imaging of the lungs: pathological versus non-pathological findings. *Radiol Med* 2017; **122:** 902–8.

37 Morgan B, Adlam D, Robinson C, Pakkal M, Rutty GN. Adult post-mortem imaging in traumatic and cardiorespiratory death and its relation to clinical radiological imaging. *Br J Radiol* 2014; **87:** 20130662.

38 Traill Z. The role of computed tomography and magnetic resonance imaging in the investigation of natural death. *Diagn Histopathology* 2010; **16:** 560–4.

39 Jackowski C, Grabherr S, Schwendener N. Pulmonary thromembolism as cause of death on unenhanced post-mortem 3T MRI. *Eur radiol* 2013; **23:** 1266–70.

40 Makino Y, Kojima M, Yoshida M, et al. Post-mortem CT and MRI findings of massive fat embolism. *Int J Leg Med* 2020; **134**(2)**:** 669–78.