

Post-mortem imaging in forensic investigations: current utility, limitations, and ongoing developments

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Abstract: Forensic imaging is a new field with increasing application all over the world. However, its role in legal medicine is controversial, mostly due to the use of undefined and unclear terms. The aim of this article is to describe forensic imaging and to explain the various techniques that pertain to it. Essentially, these methods consist of radiological methods such as conventional radiography, computed tomography, and magnetic resonance imaging, but other techniques such as 3D surface scanning are also employed. Computed tomography can be combined with minimally invasive strategies such as image-guided sampling or post-mortem angiography. We provide an overview of the advantages and limitations of these methods, which must be identified and understood to enable correct application.

Keywords: forensic imaging, post-mortem computed tomography, magnetic resonance imaging, forensic radiology, virtual autopsy

Introduction

In recent years, modern imaging methods, especially radiological cross-sectional imaging, have found their way into the daily routine of forensic practice in centers all over the world. Due to the increased use of imaging for forensic purposes as well as the establishment of specific research projects, the number of published studies in this field has increased rapidly in recent years. This new domain of research is interesting to radiologists as well as to forensic pathologists; radiologists have been involved in most forensic imaging projects from the beginning, underscoring the field's integration of two distinct medical specialties. While radiologists read the obtained images, forensic pathologists focus on findings important for medico-legal reconstructions, which are not necessarily important from a clinical point of view. Pathologists are also able to explain certain phenomena visible on images due to their knowledge of thanatology.

Although many articles have been published in radiological and forensic journals, in the early years of modern post-mortem imaging, most of these articles consisted of case reports or feasibility studies conducted on a small number of cases. Large, basic scientific studies were unfortunately missing during this early period, which is perhaps why the medico-legal community was remarkably skeptical of new post-mortem imaging methods. There was much speculation about the role of these methods and their relationship to forensic autopsy. Unclear study designs and unscientific terms were often used, leading to unsupported conclusions that were questioned. Confusion was further increased by the use of undefined or unclear terms such as "necroradiology", "forensic radiology", "virtual autopsy", and "minimally invasive autopsy", which were

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rarely explained in the articles. In particular, the term “virtual autopsy” aroused extensive discussion, as it suggests that this kind of “autopsy” replaces the conventional “real autopsy”. These issues created conflict regarding the implementation of two completely different procedures, resulting in distinct opinions on the use of imaging methods in legal medicine.

The aim of this review is to define the core concept of forensic imaging. We also present relevant technologies and their respective pros and cons, thus establishing the role of modern imaging in the field of forensic medicine.

Current methods of post-mortem forensic imaging

All of the radiological techniques currently used in legal medicine are derived from clinical practice and employ available imaging modalities. Other imaging methods can also be implemented; for example, 3D surface scanning is a technology that was adapted from the car industry. Although photography is also a part of forensic imaging, in this review, we will focus on the techniques most often categorized as forensic imaging: conventional radiography, post-mortem computed tomography (PMCT) and the minimally invasive approaches associated with it, magnetic resonance imaging (MRI), and 3D surface scanning. An overview of these methods and their respective advantages and disadvantages appear in Table 1.

Conventional radiography

Conventional radiography is the oldest radiological imaging method used in forensic medicine. In this technique, the body is investigated via direct exposure to X-rays; structures exposed to the beam are projected onto a radiographic image. The image is composed of different tonalities of black and white, corresponding to the number of X-rays that reach the detector. Contrast is possible due to the distinct absorption properties of body structures (bone is associated with high absorption and soft tissues display less attenuation). Conventional radiography employs two types of devices available in medical institutions: 1) analog equipment that uses radiological film for the impression of images, and 2) newer equipment that is completely digitized. In digital and digitized analog equipment, images are acquired in digital DICOM format, which is currently used for all imaging modalities.

Immediately after their discovery by Wilhelm Conrad Röntgen in 1895, X-rays were employed in post-mortem investigations,¹ especially in anthropology. For example, there are records of the radiography of a mummified hand of an Egyptian princess in 1896.² This example indicates that

the complementarity of forensic medicine and X-ray-based techniques was recognized from the beginning.

One of the most famous cases that employed conventional radiography occurred in 1935 in Scotland.³ Human body parts were discovered in a river and subsequently identified as belonging to two women who were probably dismembered. At the same time, the nurse and the wife of a doctor in Lancaster were reported missing. Radiological examination of the body parts enabled rapid assessment of the age and size of the two victims. Identification was carried out by superposing X-ray images of the skulls with photographs of the alleged victims. The surgical precision used to dismember the two women as well as other information suggested that the perpetrator possessed medical skills. The doctor from Lancaster was ultimately convicted of these crimes.

Conventional radiography is one of the most common imaging modalities in forensic medicine worldwide. Most forensic institutions possess their own X-ray devices, which are often used to evaluate the osseous system in cases of trauma or to characterize the presence of a foreign body. Radiography is advantageous, as it is simple to perform, rapid, and cost-efficient. Radiography is often implemented for infant corpses, for highly putrefied, charred, or otherwise altered bodies, and for bodies of unknown identity. Conventional radiography can also provide important information that is integrated with other complementary exams for age determination (Figure 1), not only of deceased but also of living persons.⁴⁻⁶ Nowadays, conventional radiography is often replaced with multi-detector computed tomography (MDCT), which allows 3D representation of any segment of the human body as well as better soft-tissue contrast. However, due to the common availability of conventional radiography and the specific indications that justify its use, such as the examination of corpses and objects that cannot be examined by CT due to a large volume, conventional radiography still plays an important role in legal medicine.

PMCT

Currently, one of the most-used radiological modalities in modern forensic imaging is MDCT. This extensive use means that the term PMCT often refers to MDCT.

Unlike conventional radiography, MDCT uses a computer to generate images that are saved in DICOM format. MDCT is based on the principle that the density of each tissue can be measured by calculating the attenuation coefficient of an X-ray beam passing through it. The body is examined through direct exposure to X-rays via a rotating tube. The attenuation values of the X-rays are expressed in Hounsfield units; these

Table I Overview of forensic imaging methods and their advantages, disadvantages, and fields of application

Method	Advantages	Disadvantages	Field of application
Conventional radiography	Fast examination Easy to handle Simple data storage Relatively low maintenance costs Visualization of the skeletal system Detection of foreign bodies	Radiation (need for specific protection for the personnel) No 3D reconstructions Very limited visualization of soft tissue Superimposed image Quality strongly dependent on acquisition	Detection of foreign bodies Identification Age estimation Changes/lesions of the skeletal system
PMCT	Fast examination Easy to handle Ideal for 3D reconstructions Relatively low maintenance costs Excellent visualization of skeletal system and gas	Radiation (need for specific protection for the personnel) Data storage Limited visualization of soft tissue, organs, vascular system Training needed for correct interpretation	Trauma cases, especially lesions of the skeletal system (accidents, falls from heights, traffic accidents, blunt trauma) Sharp trauma Gunshot trauma Child abuse Detection of foreign bodies Identification Age estimation Detection of gas embolism Changes in the skeletal system
PMCT-angiography	Minimally invasive Good visualization of soft tissue and organs, especially the vascular system Ideal for 3D reconstruction of the vascular system Method of choice to detect lesions of the vascular system	Relatively time-consuming Data storage Special training needed Costs of material	Trauma cases (accidents, falls from heights, traffic accidents) Sharp trauma Gunshot trauma Bleeding, vascular lesions Death after surgical intervention Pathologies of the coronary arteries (evaluation of stenosis) and sudden cardiac death Detection of malformations of the vessels
CT-guided sampling	Minimally invasive Low risk of sample contamination Low risk of artifacts Easy to handle	Relatively time-consuming Special training needed Data storage	Sampling of body fluids and samples of organs for toxicological, microbiological, microscopic, and immunohistochemical examinations Sampling of gas for analyzing cases of putrefied corpses, gas intoxication, gas embolism, etc
MRI	Good visualization of soft tissue, organs, vascular wall No radiation	Time-consuming More difficult to handle High maintenance costs Need specific architectural construction 3D reconstructions need special sequences Data storage Training needed for correct interpretation	Blunt trauma Sharp trauma Strangulation Child abuse Medical errors, death after surgical intervention Detection of foreign bodies Age estimation Identification
3D surface scanning	Good visualization of surface High resolution (mm) Perfect for 3D modeling, reconstructions Very low maintenance costs Mobile	Time-consuming Extensive training for handling necessary No information about inner findings Treatment of data needs a specialist	Trauma cases (traffic accidents, blunt trauma) Reconstruction of traffic accidents Comparison between injury and injury-causing object Comparison of bite marks and dental imprint Digitalization of objects (eg, bones for anthropological examination)

Abbreviations: PMCT, post-mortem computed tomography; MRI, magnetic resonance imaging; CT, computed tomography.



Figure 1 Conventional radiography of the left wrist and hand of a young, deceased, unknown person.

Note: This image was used for age estimation during identification of the body.

units are characteristic of various tissues and body fluids. Radiographic data are interpreted through the evaluation of various cross-sectional images. While 3D reconstructions are very clear and intuitive, enabling better understanding of the images for a medical layman, radiological assessment and diagnosis should always be based on axial views. Three-dimensional models are always at risk of artifacts, and the assessment of 3D models alone may cause discrete findings to be overlooked.⁷ However, these models are ideal

for illustrating findings, for example during meetings with prosecutors or police officers. Additionally, 3D models can be presented in court, as they are less impactful and personal than photos of the deceased.

As MDCT can yield spatial resolution <1 mm and offers excellent contrast, particularly for bone, it is the method of choice for assessing the skeletal system⁸ in both clinical and post-mortem imaging. The sensitivity for osseous findings is higher for PMCT than for conventional autopsy,^{9,10} mostly because the determination of many skeletal lesions is only possible through specially adapted dissection methods, including extensive maceration of the soft tissue. PMCT visualizes new and old fractures, even small ones, in poorly accessible skeletal parts such as the posterior parts of the ribs, pelvis, and vertebrae. By using 2D and especially 3D reconstruction methods, one can also identify and present complex fractures and the orientation of bone fragments in situ, without the risk of displacing them via direct manipulation (Figure 2).

CT is the ideal method for detecting radio-opaque foreign bodies. For example, it visualizes medical implants, projectiles and/or their fragments, and swallowed or aspirated foreign bodies. CT makes the discovery of small or fragmented objects much easier than does classic autopsy^{11–13} and allows rapid orientation for targeted extraction during autopsy. However, one of the most significant disadvantages of PMCT versus autopsy is its limited visualization of soft tissue, especially organ parenchyma. Thus, although PMCT is suitable for investigating traumatic⁹ death and hemorrhagic diseases such as cerebral hemorrhage, subarachnoid hemorrhage, aortic dissection, and aortic aneurismal rupture, it may not make a substantial contribution to the determination of non-traumatic death not related to hemorrhagic lesions.

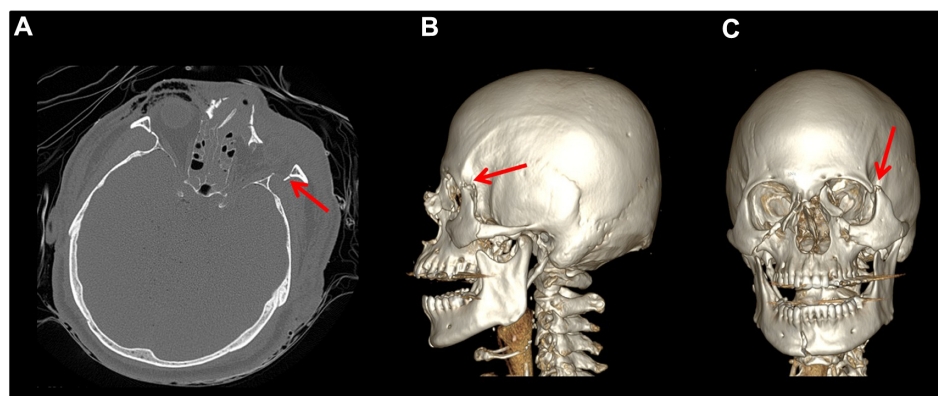


Figure 2 Visualization of bone lesions by PMCT.

Notes: Visualization of a fracture of the lateral wall of the left orbita (red arrow) by PMCT in (A) a 2D axial reconstruction, (B) a lateral view from a 3D volume rendering reconstruction, and (C) a slightly oblique frontal view from a 3D volume rendering reconstruction.

Abbreviation: PMCT, post-mortem computed tomography.

PMCT clearly depicts calcifications of the coronary arteries (Figure 3). However, it does not allow the investigator to draw any conclusions regarding patency of the vessel's lumen or associated injury to the myocardium. As no blood flow is evident on PMCT, possible stenoses or occlusions cannot be assessed, although some correlation is possible via calculation of the calcium score.¹⁴

Given these considerations, the indications of PMCT in forensic medicine are especially focused on traumatic events, such as blunt violence, falls from heights, traffic accidents, badly damaged bodies (eg, due to train or airplane accidents), gunshot incidents, and cases in which foreign bodies must be sought (after the implantation of medical material or for investigating carbonized or putrefied corpses). PMCT is also an important tool in cases of infant deaths^{15,16} as well as child and elderly abuse^{17–19} because it yields a good and rapid overview of the skeletal system. It can be useful for estimating age,^{20–22} especially for bodies that lack an identity. PMCT is one of the fastest methods for detecting the abnormal presence of air or gas, which can often be difficult to find during autopsy. Its high sensitivity to the presence of gas allows detection of even the smallest amounts of gas, including accumulations in anatomic cavities or soft tissues²³ as well as air embolism, although care must be taken to correctly interpret the origin of the gas (putrefaction gas versus exogenic gas).²⁴

Since the first report of PMCT in 1983,²⁵ the number of such investigations has risen all over the world;^{9,26–31} some

forensic institutes are even starting to use PMCT in their daily routine.^{9,10,32–34} The frequency of examinations carried out in each facility and thus the width of indications depends on the availability of MDCT units. While some institutions have no access to MDCT, some use scanners available in the radiology departments of nearby hospitals, usually outside clinical hours. In the best-case scenario, institutions have their own MDCT scanners and can screen bodies prior to autopsy.

PMCT-guided sampling

MDCT enables the visualization of anatomical structures and abnormalities deep within the human body. In clinical practice, this feature allows minimally invasive extraction of histological samples and/or minimally invasive treatment procedures via accurate localization of the lesions/structures.

The same idea can be translated to post-mortem imaging in order to obtain tissue samples from anatomic structures or lesions.³⁵ This method can be particularly useful when autopsy is denied for religious^{36,37} or legal reasons. In clinical pathology, PMCT-guided sampling enables histological examination of any organ. A typical example is the sampling of lung tissue in cases in which post-mortem angiography using oily contrast agent is performed. Because injection of this contrast agent can mimic fatty embolism, it is essential to sample lung tissue before injection^{38,39} in order to obtain an accurate diagnosis and to determine the degree of fatty embolism.

Using the same approach, liquid samples can be obtained from the body via correct localization and puncture, a process that is of great interest in legal medicine.³⁹ PMCT also enables sterile puncturing for microbiological analyses. Small abscesses can be accessed via this method; they may be easily overlooked during autopsy or may be discovered only after contamination due to dissection.⁴⁰ PMCT-guided puncture also enables toxicology of human fluids such as urine, bile, gastric contents, and other biological samples.³⁹ This approach is particularly important when no autopsy can be performed or when post-mortem angiography is carried out, since samples must be collected prior to the injection of contrast medium in order to avoid contamination.⁴¹

Minimally invasive puncture also enables the controlled collection of gas samples, which is only possible to a limited extent during autopsy. As mentioned above, MDCT is an excellent tool for detecting even the smallest gas accumulations.^{23,24,42} Although highly sensitive for gases, MDCT offers no information about the provenance of gases within the body, and therefore it does not



Figure 3 Visualization of a calcified plaque on the middle part of the right coronary artery (red arrow) in a 2D axial PMCT-based reconstruction.

Note: No information concerning the patency of the vessel's lumen can be obtained.

Abbreviation: PMCT, post-mortem computed tomography.

discriminate between ante-mortem gas due to air embolism or post-mortem accumulation due to incipient putrefaction. Frequently, the chemical analysis of gas via chromatography is necessary for a reliable diagnosis. Gas can be collected through minimally invasive punctures performed under PMCT guidance, transferred to specific sampling containers, and assayed for chemical composition^{43,44} (Figure 4). Determination of the exact composition of gas accumulations enables the accurate diagnosis of ante-mortem air embolism, decompression trauma in diving incidents, and intoxication with poisonous gases.⁴⁵

PMCT-angiography

As mentioned above, PMCT is subject to important limitations in terms of the visualization of soft tissue, parenchyma, and vasculature. In clinical practice, contrast agent is injected into the patient via venous access and transported by the blood flow to various organs. This strategy allows evaluation of the vessel lumen and yields different contrast for different tissues, allowing the visualization of abnormalities. In accordance with this model, the idea of contrast-medium administration has been translated to post-mortem imaging.⁴⁶ However, since there is no active blood flow in the vascular system of a corpse, the vessels are often nearly empty and collapsed. Additionally, vessels exhibit increased porosity post-mortem, rendering infeasible the simple injection of contrast medium used in the clinic. Large amounts of perfusion are needed in order to compensate for the lack of blood in the vascular system.⁴⁶ Specific techniques and contrast agents are therefore required for PMCT-angiography.

In the past two decades, there has been great interest in developing post-mortem angiographic methods. In recent years, several authors have proposed various techniques, most of which still remain limited to experimental investigations or to specific scenarios.^{47,48} Targeted coronary angiography, which is applied regularly, was developed separately but nearly simultaneously by two centers in the United Kingdom.^{49,50} This technique fills the coronary arteries through cannulation of the aorta via the subclavian or neck arteries. The contrast agent is injected into the ascending aorta with a pressure high enough to perfuse the coronary arteries. Anterograde progression of the contrast agent is avoided by placing a balloon in the distal part of the ascending aorta. PMCT images are acquired during or after injection.

While this technique enables selective assessment of the coronary vessels, there remains a need to visualize the vascular system of the entire body. At the present time, multi-phase post-mortem computed tomography-angiography (MPM-CTA) constitutes the most used and researched technique for post-mortem whole-body perfusion.³⁸ In this minimally invasive procedure, the vascular system is perfused by injecting a mixture of paraffin oil and Angiofil[®], an oily contrast agent designed for post-mortem use.⁵¹ In contrast to aqueous liquids, oily liquids remain inside the lumen even in the heavily modified vessels of putrefied corpses.^{46,52} Access is obtained through careful dissection of the Scarpa triangle and cannulation of the femoral vessels. Reperfusion is achieved with a specific perfusion device designed for post-mortem angiography (Virtangio[®]) that pumps the perfusion mixture into the arterial and venous systems. Grabherr et al proposed

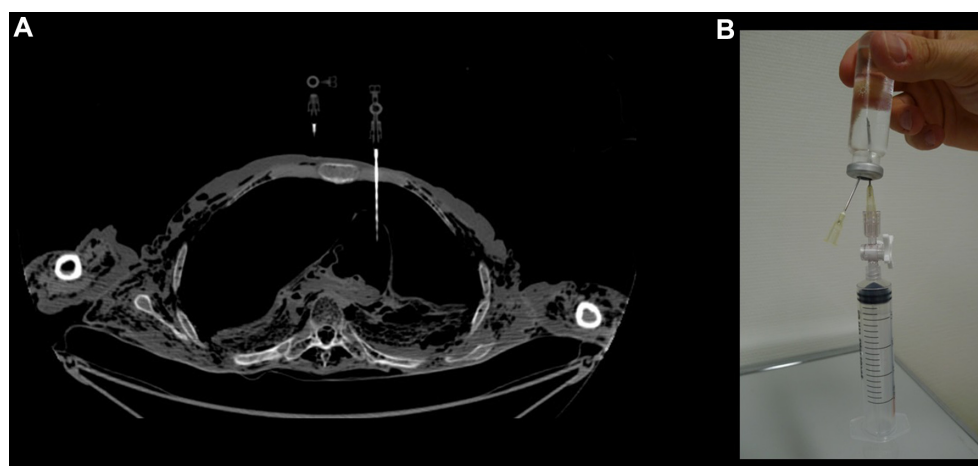


Figure 4 PMCT-guided sampling of gas.

Notes: Visualization of (A) the sampling of intra-pericardial gas and (B) injection of the collected gas into an ampoule for detailed analysis of a body with massive gas collections (a putrefied body). Note that the location of the needle tip and therefore the exact sample site is easily documented by performing PMCT with the needles in the sampling position.

Abbreviation: PMCT, post-mortem computed tomography.

a standardized method for perfusion developed on a series of 45 cases.³⁸ This method was validated in a 500-cases series,⁵³ demonstrating its advantages and limitations (particularly in comparison with autopsy) as well as its validity for application in medico-legal cases (eg, no damage of the vascular system and no dislodging of ante-mortem blood clots). MPMCTA consists of four CT acquisitions: a native scan followed by three-phase injected angiography. By comparing images acquired in the native scan with those obtained during the arterial, venous, and dynamic phases, objective conclusions can be drawn and a clinical-like diagnosis can be made. A preliminary study of 50 forensic cases described the advantages and limitations of PMCT, MPMCTA, and autopsy.¹⁰ The sensitivity of PMCT with regard to organ findings was increased up to ~81% after the injection of contrast medium, rendering it comparable with classical autopsy, which discovered 83% of all findings.¹⁰ The use of MPMCTA in in-hospital death was investigated by Wichmann et al,⁵⁴ who reported similar results.

The advantages of PMCT angiography, particularly MPMCTA, are clearly derived from clinical practice. By visualizing even small-caliber vessels, it enables accurate localization of the sources of bleeding⁵⁵ and reveals stenoses or vessel occlusions.⁵⁶ The procedure can be particularly useful in cases of death after surgical procedures, as it can exclude bleeding or yield complete assessment of all vessels.⁴⁰ It can also be suited to analysis of coronary arteries (Figure 5) and is thus an important tool for investigating the causes of natural cardiac death,^{57–59} guiding autopsy and histological sampling. Another major advantage of the technique is its clear visualization of the trajectories of stabbings and

gunshots after contrast administration.⁶⁰ MPMCTA-acquired images are particularly suitable for 2D and 3D reconstruction of these trajectories, which are very useful in court. Other PMCT-angiography-based methods can be applied for detecting vascular injuries due to stabbing or gunshots.^{61–64}

MRI

In contrast to PMCT and conventional radiography, MRI involves no ionizing radiation; it is based on the principle of nuclear magnetic resonance. When a patient is placed in a magnetic field, the hydrogen protons in the body align with the field. A radiofrequency pulse is emitted from the scanner, exciting specific atomic nuclei and rotating the protons to a 180° position. As the energy from the pulse decreases, the protons return to their initial state within the magnetic field and generate an MRI signal that is digitally transformed into images. The interval between arrival in the initial state and signal emission is called the relaxation time. Contrast between anatomical structures is possible due to the specific relaxation time of atoms within each tissue.

MRI offers high spatial resolution as well as excellent soft-tissue contrast, as it distinguishes muscles, fat, parenchyma, and neurological structures. It therefore complements PMCT, which has severe limitations due to a lack of discrimination in organ findings.

For this reason, MRI is of special significance for the diagnosis of natural death^{65–67} and for the assessment of traumatic soft-tissue injuries^{68–70} such as impact injuries after a traffic accident. In general, MRI is recommended in cases of blunt force, stab wounds, medical errors, and age estimation.^{20,71,72} It may be useful for detecting foreign bodies,⁶⁹ but

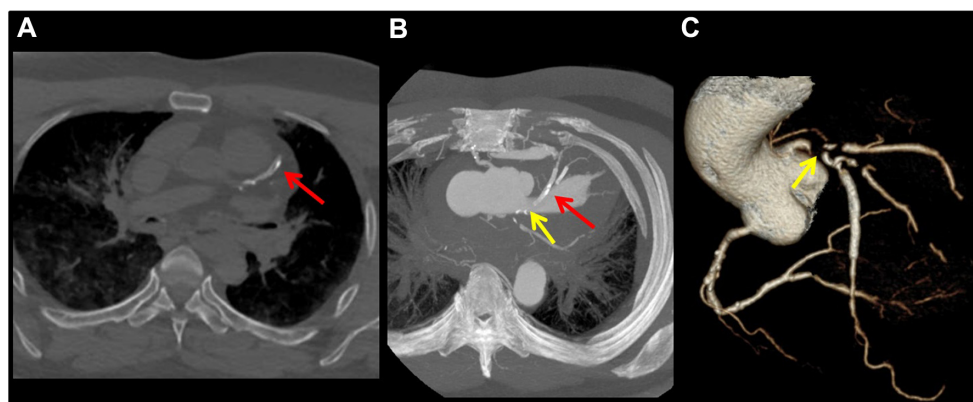


Figure 5 Images obtained from the arterial phase of MPMCTA in a case of sudden death of a person known to have a long history of coronaropathy and a coronary stent. **Notes:** Visualization of an intra-stent calcification (red arrow) on the left anterior descending artery in (A) a 2D axial reconstruction and (B) an axial maximum-intensity projection reconstruction. Also note the visualization of several filling defects of the lumen on the trajectory of the left anterior descending artery (yellow arrow) in (B) an axial maximum-intensity projection reconstruction and (C) a 3D volume rendering reconstruction of the coronary arteries. Filling defects that are stable during phases of MPMCTA indicate the presence of sub-occlusive vascular stenosis.

Abbreviation: MPMCTA, multi-phase post-mortem computed tomography-angiography.

with certain restrictions concerning ferromagnetic materials that could interact with the strong magnetic field. However, similar to PMCT-angiography, MRI yields valuable data for identifying strongly altered bodies, although the tool of choice for this indication is PMCT.

Today, MRI is successfully used by several institutions for investigations of malformations that cause death in infants and neonates.^{73–75} In such cases, which often occur outside of a medico-legal context, parents often do not consent to autopsy of the child, and thus MRI is the best alternative for documenting the cause of death. In addition to the benefits described above, MRI is an essential tool for cases of child abuse,^{76,77} as it strongly contributes to the detection of injury to soft tissue or organs.

In legal medicine, MRI is important for the assessment of cardiac pathology, especially in cases of sudden death. The myocardium must be examined in order to achieve complete cardiac imaging; MRI is the most sensible imaging modality in this regard. MRI accurately detects infarcted or ischemic regions in the heart muscle as well as fibrotic myocardial lesions, enabling early diagnosis of heart arrest. Peracute infarcted regions were previously detected with the help of MRI,⁶⁷ although these regions are not evident (macroscopically) during autopsy or (microscopically) during histology. However, further investigations are needed in order to validate the use of MRI in post-mortem cardiac assessment, especially in terms of the immunohistochemistry of MRI-based suspicion of ischemic cardiac disease. In this context,

increasing emphasis is placed on research into post-mortem MRI of the heart.^{78,79}

In clinical forensic medicine, MRI is excellent for injury assessment in victims of violence.⁸⁰ The absence of ionizing radiation allows the examination of patients even without a clinical indication. Given its high diagnostic value for soft tissues, MRI is now particularly indicated for the examination of internal findings in survivors of strangulation (Figure 6).^{81,82}

Although MRI is excellent for examining the interior of a corpse, it is not used widely in modern forensic imaging, mainly because MRI scanners are less available than MDCT devices. The acquisition, maintenance, and handling of an MRI unit are very expensive and time-consuming, so few centers of legal medicine have their own MRI equipment. The reading and reporting of MRI-acquired images are considerably more complex than those of PMCT images; hence, well-trained personnel with specific expertise are required. In comparison with PMCT, which can be performed in clinical radiology departments after routine work, MRI requires a longer period of acquisition and the costs associated with it are considerably higher.

3D surface scanning

As mentioned above, not all forensic-imaging techniques originated from radiology. Three-dimensional surface scanning is a technique that was developed for the car industry; it is extensively used for forensic investigations in Switzerland

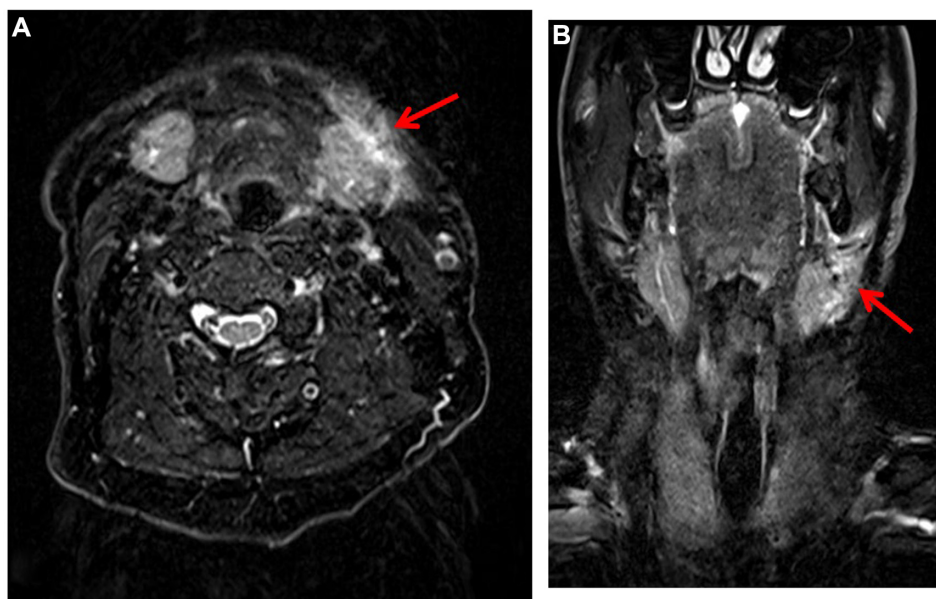


Figure 6 MRI of a victim who survived strangulation (~1 day after the aggression) in order to examine the profound structure of the neck.

Note: Visualization of a trauma-based soft-tissue edema (red arrow) in the left submandibular region on (A) a T2 axial view and (B) a T2 coronal view.

Abbreviation: MRI, magnetic resonance imaging.

by police and medico-legal institutions. Its main fields of application are the reconstruction of traffic accidents,⁸³ the correlation of a lesion and the presumed injuring-causing instrument,⁸⁴ and the comparison of bite marks with dental models of the supposed perpetrator.⁸⁵

The surface scanners used in forensic medicine are called “fringe light scanners” and usually consist of a projector with one or two cameras. During the scanning phase, stripes of different size and distance pass behind the object like slides in a slide projector, creating the impression of movement due to the play of striped light over the surface of the object to be documented. The stripes are distorted during this process in accordance with the shape of the object, and this deformation is recorded with cameras. The device is connected to a computer, which is equipped with software for calculating 3D coordinates on the surface of the object over a very small distance. Calculation of these point clouds is based on the principle of triangulation. Powerful scanners calculate up to 16 million points on the surface of the object. Complex objects are completely digitized by repeatedly scanning at various angles and distances. Predefined reference marks fixed on or around the object enable merging of the individual scans into a single data set. At the end of the digitization process, the object is shown as a 3D model in digital form at high resolution. Various 3D modeling programs allow subsequent merging and overlaying of scanned objects for comparison of their structures (eg, comparison of

a lesion on a body with the suspected injury-causing instrument; Figure 7). Today, fringe-light scanners have spatial resolutions of up to 0.017 mm. Three-dimensional surface scanning can be combined with other imaging techniques such as photogrammetry, PMCT, and MRI, for example for reconstructing complex traffic accidents.⁸³

According to its users, this technology is associated with numerous advantages. Three-dimensional surface scanning has been reported to be an objective, non-invasive method for 3D digitization of objects with high accuracy and resolution. It is relatively quick and easy to perform and allows data storage for later use or data exchange.⁸³ However, 3D surface scanning also has limitations. Since the technique was originally developed for use in industry, certain applications in the software are not suitable for forensic purposes. For example, the scanner is optimized for flat surfaces; it was not designed for use on surfaces such as skin.⁸⁶ Although repeatedly declared “easy to carry out”, result quality strongly depends on the experience and skill of the user, particularly for event reconstruction and for comparing two objects.⁸³ Thus, the “objectivity” of the method, which is often emphasized in publications, should be interpreted with caution. In our experience, the device is very sensitive to light and motion. The duration of the digitization of an object therefore varies widely and can increase significantly under inappropriate conditions. For example, the scanner has difficulty detecting a very dark or reflective surface, perhaps causing it to be

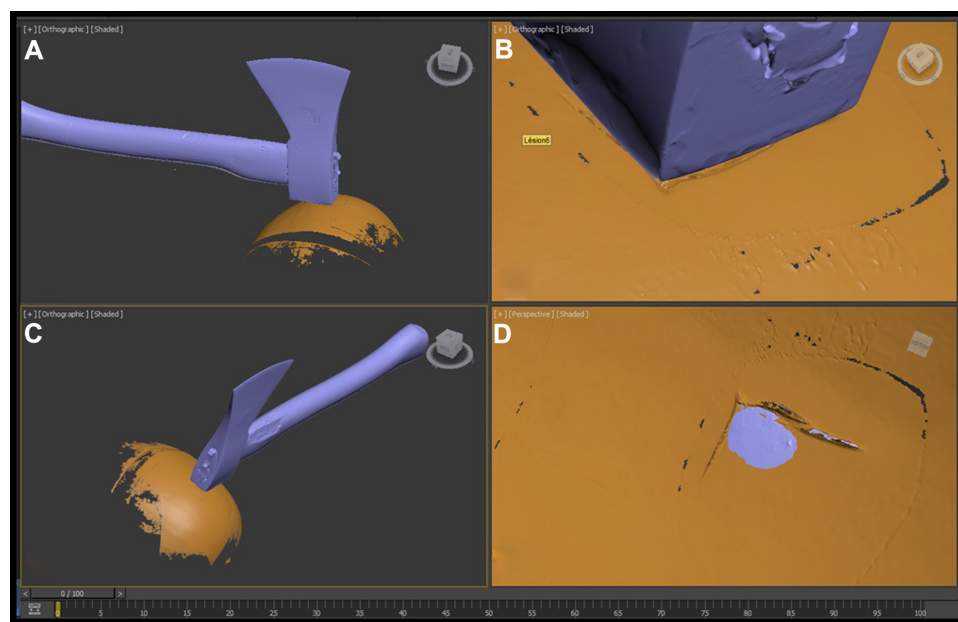


Figure 7 Visualization of the comparison of two 3D models obtained by surface scanning using a fringe-light scanner (Gom ATOS Compact Scan 5M, GOM mbH, Braunschweig, Germany).

Notes: To test the accuracy of the method, “lesions” on watermelons were produced with various instruments. Images show comparisons of the impact site on the melons’ surface and an axe. (A–C) Views of a reconstructed impact between the axe and the watermelon. (D) Imprint of the back part of the axe on the surface of the watermelon.

represented as a hole or a defect in the digital 3D model. This problem can often be resolved by applying special sprays, but these sprays are not applicable to all objects.

Despite these limitations, surface scanning and 3D modeling is an extremely impressive and useful tool for forensic imaging, with demonstrated advantages in several situations. When used properly, this technology may be key to solving complicated reconstructive questions. It undoubtedly will be improved and become widespread in the future.

The role of forensic imaging in legal medicine

Forensic imaging allows non-invasive or minimally invasive detection of several findings that may or may not be visible during classical autopsy. Digitization of bodies and objects is also possible through forensic imaging. However, a single procedure may not be sufficient for assessing a broader spectrum of findings, motivating the combination of methods for digitization of all findings. Imaging can yield information about findings for later confirmation during autopsy and guide the forensic pathologist to focus on a structure of interest, but it can also visualize lesions that would be impossible to discover and diagnose via standard autopsy alone (for example, detecting multiple small bleeding sources with PMCT-angiography).

Direct comparison of autopsy findings and imaging findings is not easy. Each technique has its advantages and disadvantages,^{9,10,84,87} and the sensitivity and specificity of imaging versus autopsy depend on the modality used and the case itself.^{10,88,89} Classic autopsy has its own strengths and weaknesses; in current practice, its value is enhanced by adding complementary techniques in order to establish a correct diagnosis. While some findings are directly evident in the autopsy room, many elements cannot be defined until further investigations are conducted, such as histological, microbiological, or toxicological examinations.

Similarly, one imaging modality or technique alone often does not lead to a precise diagnosis. Simple native CT may sometimes be sufficient to define all major findings necessary for identifying the cause of death, but not in most cases. For example, PMCT can be most accurate in a case of death due to a gunshot to the head; PMCT defines the entry and exit wounds, the presence of a projectile or fragments of it, the extent of cerebral lesions, and the trajectory of the bullet. It also predicts the vitality of the traumatic event by visualizing bronchoaspiration and gas embolism. However, regarding gunshot injury in the context of suicide, PMCT alone cannot exclude a pre-existing illness that perhaps motivated

the suicide in the first place. In some cases, autopsy alone cannot address all issues, as it detects certain pathologies macroscopically without determining whether the pathology is benign or malignant in nature. Further investigations, particularly histology, are helpful in this regard. Toxicology assists in the determination of whether the person was under the influence of alcohol or drugs at the time of death.

Examination accuracy and the need for further investigative techniques always depend on the forensic question posed in each case. For each specific question, one or several methods can be used based on their availability. It is up to the forensic pathologist to choose the most accurate method for each case and to consider the advantages and disadvantages of each modality. The pathologist must establish an equilibrium between exam quality and the need for complementary analyses. Currently, the pathologist achieves the state of the art by selecting and combining “new” and “old” methods in order to optimize the investigation for each case. However, the choice of method(s) not only depends on the pathologist, but also on the availability of devices, personnel, and funds.

As described in this review, a variety of techniques for forensic imaging are currently available. Rigorous scientific research has demonstrated that depending on the medico-legal question, forensic-imaging techniques can be superior to classical autopsy and should therefore be applied, if possible in combination with other classic or newer methods. Although modern research relentlessly introduces new techniques, we believe that in order to increase the impact of forensic imaging, more forensic pathologists should be trained and forensic-imaging techniques should be made more readily available. Training forensic pathologists to apply and understand the technologies discussed here allows them to implement these methods in their daily casework and motivates them to create networks to increase the availability of these techniques. Forensic and legal medicine must be kept up to date because, depending on the questions that must be solved, classic autopsy alone can no longer be considered the gold standard.

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Disclosure

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