Forensic imaging in Denmark, 20-year-experience

Status and future directions: A positional statement from the Danish Forensic Imaging Group of the Danish Association of Forensic Medicine

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Published in:
Forensic Imaging

DOI:
10.1016/j.fri.2024.200583

Publication date:
2024

Document version:
Final published version

Forensic Imaging 36 (2024) 200583

Contents lists available at ScienceDirect

Forensic Imaging

journal homepage: www.sciencedirect.com/journal/forensic-imaging

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A positional statement from the Danish Forensic Imaging Group of the Danish Association of Forensic Medicine

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ARTICLE INFO

Keywords:
PMCT
PMMR
PMCTA
VPMCT
3D models
Photogrammetry

ABSTRACT

In Denmark, post-mortem CT scanning (PMCT) was introduced over 20 years ago. The Department of Forensic Medicine, University of Copenhagen, implemented whole-body CT scanning before each autopsy in December 2002, followed by the Department at University of Southern Denmark in Odense in 2006 and at the University of Aarhus 2008. Subsequently, other equipment, including Magnetic Resonance (MR) scanners, surface scanners, photogrammetry equipment and 3D printers, were introduced in the following years. In this review, we will provide contemporary insights into the status of forensic imaging in Denmark, including requisitioned work and research. We will also discuss future directions in the field.

Introduction

Forensic imaging is a relatively new field that emerged approximately 20 years ago and has experienced rapid development. In 2011, the International Society of Forensic Radiology and Imaging (ISFRI) [1] was established, and in 2013, the first specialized journal on the topic, "Journal of Forensic Radiology and Imaging" (now "Forensic Imaging"), was introduced [2].

In Denmark, post-mortem computed tomography scanning (PMCT) was introduced over 20 years ago. The Department of Forensic Medicine, University of Copenhagen, implemented whole-body CT scanning before each autopsy in December 2002 [3], followed by the department at University of Southern Denmark in Odense in 2006 [4] and at the University of Aarhus 2008 (L.W.T. Boel, personal communication). In 2006 a meeting was organized with Gill Brogdon in Copenhagen to explore the potential of this tool in forensic pathology (P. M. Leth, personal communication). Subsequently, other equipment, including Magnetic Resonance (MR) scanners, surface scanners, photogrammetry equipment and 3D printers, were introduced in the following years.

The forensic pathologists and researchers at all three departments have been actively promoting the field of forensic imaging, participating as active members of ISFRI and its working groups, such as anthropology [5] , DVI [6,7], and pediatrics [8]. They have contributed by writing commentaries and letters to various journals [9–11], providing recommendations and reviews [12–21], and contributions to international textbook [22–25] and several edition of the Danish textbook "Nordisk Lærebog i Retsmedicin"(Nordic Textbook of Forensic Medicine) edited by Jørgen Thomsen [26].

In 2015, Professor Peter Mygind Leth, chief forensic pathologist at department of forensic medicine at the University of Southern Denmark, served as the president of ISFRI and organized the annual conference that year at the University of Southern Denmark in Odense with 182 participants from 25 countries. The main topic of the congress was "Forensic imaging in times of terror" and 23 oral presentations and 32 poster presentations covered a broad spectrum of forensic imaging applications. Forensic imaging has been a relevant topic at annual meetings of the Danish Association of Forensic Medicine ("Dansk Selskab for Retsmedicin"), where the utility of PMCT and 3D imaging technologies has been presented theoretically and practically to researchers and stakeholders, including Danish authorities.

In 2021, the "Danish Forensic Imaging Group" was established under the umbrella of the "Danish Organization of Forensic Medicine"("Dansk

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https://doi.org/10.1016/j.fri.2024.200583

Available online 16 February 2024

Selskab for Retsmedicin") was formed with representatives from each of the three Danish forensic departments. The group aims to enhance forensic imaging practices, facilitate knowledge exchange, and promote advancements in the field, encompassing public sector services to the policework, research, development, education, and communication.

In this overview, we will provide contemporary insights into the status of forensic imaging in Denmark, including requisitioned work and research. We will also discuss future directions in the field.

Organization of the departments of Forensic Medicine in Denmark

In Denmark, there are three departments of Forensic Medicine, each affiliated with a different university: the University of Copenhagen, the University of Aarhus, and the University of Southern Denmark (Odense). The three forensic departments are accredited as an inspection body according to an international (ISO/IEC) and European (EN) standard that is approved by the Danish Standards (DS): DS/EN ISO/IEC 17020:2012. Danish forensic medicine is accredited by the Danish Accreditation Fund (DANAK) and detailed procedures and standards are constantly updated and reviewed.

Forensic examinations, which include medico-legal external examinations, forensic autopsies, clinical forensic medicine examinations, forensic odontology investigation and forensic anthropology analysis, are carried out for the police, the Independent Police Complaint Authority, the courts, the Danish health regions, and other authorities in Denmark, Greenland, and the Faeroe Islands. Each department is responsible for a specific geographical area, as follows:

- The department at Copenhagen covers the region of Zeeland and the islands of Bornholm, Lolland, Falster, and Møn. The population in this area is approximately 2.5 million, and the department performs around 700 PMCT/ autopsies annually.
- The department at Aarhus is responsible for the region of Middle and Northern Jutland, which is home to approximately 2.2 million people. The Aarhus department conducts around 400 PMCT/autopsy annually.
- The department at Odense serves the area of Fyn and Southern Jutland, which has a population of approximately 1 million. It performs approximately 200 PMCT/autopsies each year.

Imaging equipment, software applications and personnel (requisitioned work and research)

A quick overview of imaging equipment and software used in the three departments is provided in Table 1. CT scanners, X-rays machines (including those for teeth), 3D printers, and to some extent photogrammetry, are used in the requisitioned work. Micro CT, Magnetic Resonance (MR) scanning, surface scanner, and 3D digitizers are currently reserved for research purposes and not utilized in requisitioned cases. Due to the varying complexities of the equipment, only a few individuals possess the necessary competences to operate them, as shown in Table 2. Through collaborations with other Danish Universities, the departments gain access to advanced imaging instruments, such as micro- and nano-CT scanners and electron microscopes, which are not already available in-house. Additionally, we can rely on the services of specialized centers, like the "3D Printcenter" at Aarhus University Hospital, which facilitates 3D printing services.

PMCT and its applications in requisitioned work

PMCT is performed in all cases requested for forensic autopsy. Medico-legal external examinations are conducted by the police in collaboration with a doctor from the Danish Patient Safety Authority, or, in the Copenhagen area, a forensic pathologist as delegate. The doctor advises the police whether forensic autopsy is warranted and is

Table 1
Equipment/ software at the three departments.

Equipment /software	Copenhagen	Odense	Aarhus
CT scanner* Software*:	Siemens Somatom Definition, Myrian [27] / Mimics [28]	GE Revolution Ascend with 72 kW generator	Canon Aquilion Prime SP 160 Slice, Vitrea Base version 7.14.4* / 3D-Slicer [29] / Horos [30] / Fiji [28]
X-ray* Software*:	Dragon, Dental X-ray: Planmedica Prox Myrian		Siemens Mobilett XP Fuji FDR-Go Flex Dental X-ray: NOMAD CE VixWin
Micro CT			TESCAN CoreTOM
MR scanner Software:	Siemens Essenza 1,5T Myrian [27]		Phillips Ingenia 1.5T (via. Collaboration with Hospital Dept.) Vitrea Base version 7.14.4 3D-Slicer [29] / Horos [30] / Fiji [28]
Surface scanner Software	Next Engine, Artec Eva	Artec Spider	PrimeScan (dedicated for dental scanning)
3D digitizer Photogrammetry: camera Photogrammetry: software	3D MicroScribe Canon 5DSr* equipped with 50 mm lens or 100 mm macro lens. Photomodeller [31]* 3D Zephyr [32]		Canon EOS 60D equipped with 100 mm macro lens. Canon G16 Iphone 13 mini Meshroom [33]
3D printer Software	2 x Ultimaker Extended 2*	Raise 3D Plus 3D-printer	Sinterit LisaPro* Blender [34] / Netfabb Premium [35]* / Sinterit Studio [36]*

* Used in requestioned work.

responsible for issuing a death certificate. The police decide, based on the case-info, whether to perform a forensic autopsy. PMCT is only acquired in connection to the autopsy, that is after the police has decided to proceed with a forensic autopsy. Routinely, PMCT is performed without contrast and ventilated PMCT (VPMCT). At the department of Forensic medicine in Aarhus, angiography PMCT and VPMCT can be performed when suspected feasible for individual cases. An overview of the workflow of the department is illustrated in Fig. 1. There can be small "divergences" at local level. A national project is currently investigating the possibility to implement PMCT as part of the medico-legal external examination (see below, the paragraph "Research in forensic imaging in Denmark", for more information).

Dependent on the department, prior to autopsy, the PMCT images are reviewed and interpreted by either the doctors responsible for the cases, which typically include a resident doctor and their supervisor (a senior forensic pathologist), and/or by either a radiologist or forensic radiographer, both with specialized training in forensic imaging, which inform the autopsy-team about relevant findings. The main findings of the PMCT are briefly described in the autopsy report. A pediatric radiologist always performs the reading of the full skeletal X-rays of children.

PMCT images can also be used for supplementary analyses, such as identification by means of the teeth (Forensic odontology identification), 3D visualizations, and following segmentation also 3D printing.

Table 2
Equipment and personnel who have the competence for using the equipment.

Equipment	Copenhagen	Odense	Aarhus
CT scanner	Radiographer (1) Autopsy technicians (6) Anthropologist (1) Forensic pathologists (2) Research personal (1)	Radiographer (1) Autopsy technicians (2) Anthropologist (1) Forensic pathologists (2)	Radiographer (1) Autopsy technicians (3) Research personal (1) Forensic pathologists (1)
X-ray dragon Dental X-ray	Radiographer (1) Autopsy technicians (6) Anthropologist (2) Forensic pathologists (1) Forensic Odontologist (2)		Radiographer (1) Forensic Odontologist (2)
Micro-CT			Radiographer (1) Research personal (1)
MR scanner	Radiographer (1) Autopsy technicians (6) Anthropologist (1) Forensic pathologists (2)		Radiographer (1) Research personal (1)
Surface scanner	Anthropologist (1)	Anthropologist (1)	Forensic Odontologist (2) Research personal (2)
3D digitizer	Anthropologist (1)		
Photogrammetry	Anthropologist (2)		Research personal (1)
3D printer	Anthropologist (1)	Anthropologist (1) Forensic pathologist (2)	Research personal (1) Forensic pathologists (1)

Forensic odontology identification

When there is doubt regarding the identity of a deceased, comparison between antemortem (AM) and postmortem (PM) dental records is performed by a forensic odontologist. In Copenhagen, a complete dental registration is performed using the PMCT images following the guideline described by Jensen et al. [19] and compared with the AM imaginary material available. In Aarhus the forensic odontologists take their own special radiographs and do not rely on the PMCT. There are two forensic odontologists at each of the three departments.

Advanced 3D visualizations

In relevant cases, more often in homicide cases, advanced 3D visualization of injuries can be created using PMCT images [37]. Specialized imaging post-processing software such as Mimics or 3D Slicer or Vitrea allows for the generation of 3D models depicting bones, internal organs, and bullet paths. Blender is another software used for visualizing and manipulating 3D models. Specifically, it was employed at the department at Aarhus to illustrate a case of dismemberment (L.W.T. Boel, personal communication). This These highly detailed 3D models offer a comprehensive visual representation of the injuries, significantly enhancing the comprehension of complex findings [38]. The resulting images are collected into a supplementary document containing relevant images, which is provided along with the autopsy report to the Danish police.

3D printing

3D printing has been utilized only four times in Danish courtrooms. The first instance occurred in 2017, followed by another case in 2020, and finally, two times in 2022. All cases entailed complex cranial trauma. The rationale behind using 3D models was for the forensic pathologist, serving as expert court witness, to facilitate the explanation of autopsy findings to jurors, judges, prosecutor, and defender. In all instances, the 3D models were presented by forensic pathologists during their testimony, who used them to highlight different findings. In Denmark, we do not provide 3D print models directly for the Danish Police or judicial system, but solely for use as supportive tools at witness calls. This decision has been strengthened through discussions in the “Danish Forensic Imaging Group” as we firmly believe that the utility of 3D printed models is optimal when they serve as supportive tools for expert witnesses with extensive knowledge about the pros and cons of forensic 3D-prints. We recently conceived a study which found that the benefit of 3D prints in the Danish court rooms appears to be relatively limited, because the members of the jury focus more on the expert witnesses interpretation of the case material than on their own ability to understand details visualized using 3D printing [39]. Nonetheless, we believe that 3D printed models do provide value as mediators for relevant discussions, and potentially for creating custom-tools to aid autopsy in certain cases [40].

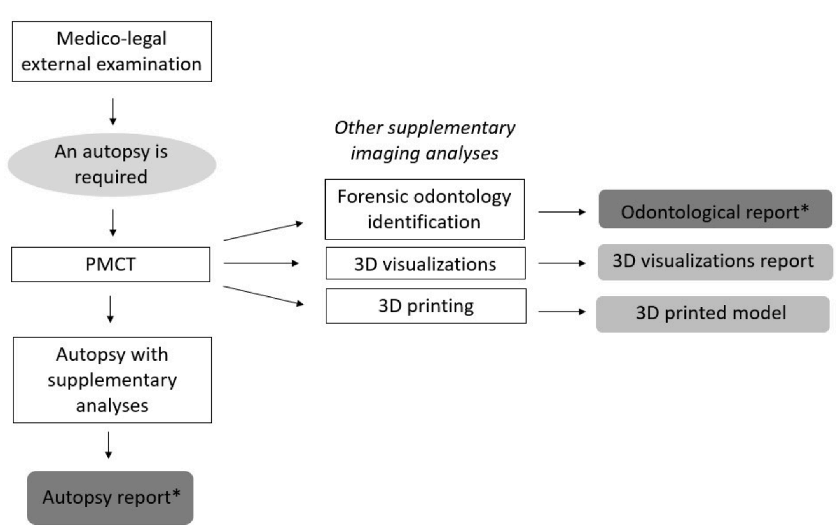

Fig. 1. Workflow of the requisitioned work.*Independent reports

Photogrammetry and its application in requisitioned work: estimation the stature of perpetrators

At the Department of Forensic Medicine in Copenhagen, we employ photogrammetry techniques to estimate the height of suspects from videos [41–44]. This analysis proves valuable in identifying criminals captured by surveillance cameras, especially when the perpetrator's height significantly deviates from the average population height. The process involves creating 3D models of the relevant area using photogrammetry, allowing us to orient and scale the video frame featuring the suspect(s). From these data, we extract measurements to provide an estimated height range for the suspect. The estimated height is expressed as an interval, which can vary from ± 4 cm to ± 15 cm. This range considers several factors that can influence stature estimation including technical uncertainties due to video quality and frame orientation precision, uncertainties related to the suspect's posture (as individuals rarely stand in an upright position with feet together and knees extended), and uncertainties arising from any headwear or footwear the suspect may be wearing. These analyses are performed by forensic anthropologists.

Forensic age estimation in living

Forensic age estimations of living individuals, encompassing age estimation cases from Denmark, are conducted at the department in Copenhagen [45]. Typical cases involve asylum-seeking unaccompanied children, while few cases pertain to criminal responsibility and victims of human trafficking.

Age is estimated based on dental development, bone maturation of the left hand-wrist, and secondary sexual development. A conclusive age estimate, presented as an age range, is obtained by combining the minimum and maximum results from these two examinations, i.e., "bone age" and "dental age".

The assessment of root and crown development is conducted by a forensic odontologist using the 10-point staging technique developed by Gleiser and Hunt and modified by Köhler et al. [46]. The most likely age-range is derived from reference studies by Köhler et al. [46], Haavikko [47], and Mincer et al. [48].

Bone age is estimated from a radiograph of the left hand-wrist, and a pediatric radiologist from the Danish National Hospital (Rigshospitalet), a highly specialized hospital in Denmark, evaluates bone maturation by comparing the radiograph to the standards of the radiographic atlas of bone maturation by Greulich and Pyle [49].

The physical examination is performed by a forensic pathologist and includes anamnestic information regarding the general health status, height, and weight measurements, along with a visual assessment of secondary sexual development according to Tanner [50]. The main purpose of the physical examination is to exclude current or past illnesses or living conditions which might have impacted growth and development. Examination of the clavicle, knee, or other bones is conducted [45].

Research in forensic imaging in Denmark

The Danish forensic departments have played a proactive role in the field of forensic imaging research. The extensive utilization of medical imaging and 3D technologies has been rigorously examined across a spectrum of disciplines, encompassing forensic pathology, forensic odontology, and forensic anthropology. Our research has consistently drawn inspiration from method developments aimed at practical application in routine procedures, as well as developing techniques and methods to advance the field itself. Many innovative ideas and projects aimed at enhancing existing procedures have been based on challenges encountered during routine work. Here, we provide a comprehensive overview of the key themes that have been the focus of our research over the past two decades.

Autopsy and PMCT

Like forensic researchers worldwide, we too sought to address significant research inquiries. These encompassed the following pivotal questions:

- Can autopsy and PMCT yield comparable information?
- Can the cause of death be determined through PMCT?
- In what circumstances and ways can PMCT surpass autopsy?
- Is PMCT a feasible substitute for traditional autopsy?
- Who should undertake the evaluation of PMCT results?
- Can angiography and ventilation techniques enhance the visualization of PMCT findings?

One year after introducing PMCT prior the autopsy in Copenhagen (in 2003) the experiences indicated that PMCT was a helpful supplement to the medico-legal autopsy, especially in traumatic cases [3]: it was especially useful in cases of intracranial hemorrhages, cerebral contusions and edema, splenomegaly, pelvic fractures and extremity fractures and aneurysms, both intracranial as well as aortic. It was observed that a forensic pathologist without specialized radiological expertise could review PMCT images, however, it was clear that the quality of interpretations depended on the examiner's experience. Recommendation was also made to reduce the slice thickness in head scans. Similar experiences were documented in Odense [4,51]; Leth emphasized PMCT's usefulness in identification cases, such as mass disasters, as well as instances involving battered children, gunshot wounds, and traffic accidents. Leth noted that CT enabled investigation of anatomical regions not easily accessible through autopsy, and its digital documentation proved easily storable, allowing reviewing by others. Additionally, CT images were considered potentially more suitable for courtroom presentation than traditional autopsy photos.

Several years later, Leth and Thomsen [52] conducted a prospective double-blind analysis covering a wide timeframe (2006–2011), involving 900 cases. They confirmed that PMCT was a valuable supplement to autopsy and could serve as a screening tool for selecting cases suitable for autopsy. Their findings indicated that PMCT and autopsy concurred on the cause of death in approximately two-thirds of cases, with the highest agreement observed in traumatic deaths. Furthermore, they stated that: "PMCT reliably detected air and fluid collections, hyper-and hypotrophy, fractures, neoplasms, gallstones and kidney stones, calcification, foreign bodies, aneurisms, hernias and cerebral hemorrhages and was less reliable at detecting injuries in inner organs, small hematomas and vessel transections. PMCT was unable to detect thrombosis, thromboembolism, cirrhosis, esophageal varices, myocardial infarctions and myocardial scar tissue, peritonitis and gastro-intestinal ulcerations" [52]. A comprehensive summary of Odense's experience with PMCT has been described in the doctoral thesis in medicine by Leth [53].

The benefits and drawbacks of PMCT have also been explored in relation to specific categories of manners of death, including homicides [54], traffic incidents [55–57] and drownings [58,59].

Comparative studies between PMCT and autopsy were conducted for instances of skull trauma [60–63] and cervical spine injuries [56,64,65].

The potential of PMCT was also examined in assessing the density of the myocardial tissue in the left ventricle of the heart [66], in detecting calcium deposits within the coronary artery [67] and in quantitatively evaluating pulmonary structures response to different ventilation pressures [68].

Over the years, we have encountered numerous intriguing cases that we have also published [69–80]. Among them, the most unusual case worth mentioning is the one with the giant bullae: the severity of the lung disease was clearly visible on CT but might have appeared less severe at autopsy, or at least been difficult to assess [76].

PMCT angiography and ventilated PMCT

The utilization of whole-body PMCT angiography (PMCTA) or focused/partial PMCT angiography has been recommended, as highlighted by van Rijn and Leth [15]. At all three departments, significant efforts have been directed towards the development, utilization, and validation of this technique. Various tests were conducted, including studies on eviscerated hearts [12,81], in-situ hearts [82], upper extremities [83], and whole-body [84].

Additionally, the evaluation of an alternative contrast agents was undertaken. Haakman et al. [84] explored the potential of a barium sulfate suspension combined with polyethylene glycol, at a concentration of 20 %, as a contrast agent to effectively visualize microvascular structures, yielding positive outcomes.

Naturally, the validation of imaging outcomes was carried out through histology [84] or autopsy [83]. An interesting study proposed and tested a methodology to align images from PMCTA, optical coherence tomography, and histology for the analysis of calcified coronary plaques [85]. On the other hand, PMCT without contrast was used to assess the accuracy of the Agatston score in determining coronary artery calcification [82].

The application of ventilated PMCT (VPMCT) is not a routine at the forensic departments in Denmark. At the Department of Forensic Medicine in Aarhus, one study has identified the optimal pressure for VPMCT, aiming to replicate the conditions of a clinical breath-hold CT scan, and developed a customized, straightforward, and cost-effective inflation device, which could potentially find utility during postmortem magnetic resonance (PMMR) ventilation as well [68]. The study is in line with other projects from the department that aimed at improving pulmonary PMCT [14].

Post-mortem Magnetic resonance (PMMR) imaging and its applications

Magnetic resonance imaging provides, also in a post-mortem setting, great intrinsic soft tissue contrast compared to PMCT (i.e., without contrast). Accordingly, MRI has profound potential for several forensic imaging applications, despite technical intricacies and a time-intensive nature of MRI, where especially setting up protocols requires special knowledge. While clinical radiologists have collaborated in designing our studies to formulate these protocols, their understanding is often limited to living subjects and may not encompass factors unique to working with the deceased, such as the influence of low temperatures and intracorporeal postmortem gas development. However, the engagement of radiographers and researchers with MRI-experience from projects outside the clinic in our teams over the last decade has proven beneficial in facilitating the planning and execution of more PMMR projects.

At the Department of Forensic Medicine in Copenhagen, we have employed MRI in a study focused on age estimation of subadults, specifically investigating the ossification stages of clavicles [45] and knees [86]. Hearts were also imaged using PMMR, although challenges related to sedimentation hindered the utility of PMMR in effectively visualization [17]. More recently, PMMR has been employed to examine long bones and to compare the 3D models obtained from both CT and MR scans (C. Villa, personal communication).

At the Department of Forensic Medicine in Aarhus, the feasibility of utilizing diffusion tensor imaging (DTI) has been explored [83,87]. This technique holds the potential to identify peripheral nerves, offer detailed characterization of nervous tissue structures, and assess microstructural properties. Experiments were conducted on subjects to examine the architectural arrangement of the lumbosacral nerves [87] as well as the cervical spine and its associated nerve roots [88].

Beyond 2D visualizations

Both PMCT and PMMR imaging offer the potential to acquire volumetric measurements of bones and organs. The resultant 3D models generated from these imaging methods can be employed in advanced quantitative analyses. PMCT-derived 3D models have proven useful for determining organ volumes, e.g. liver and heart [89], and for quantifying the volume of epicardial adipose tissue [90]. The creation of 3D models representing air and liquid volumes is also possible, as evidenced by the successful segmentation of fluids within paranasal sinuses [59]. Quantitative PMCT approaches, drawing on stereological principles for unbiased volumetry, has been applied to quantify pulmonary structures, which would be difficult to quantify using other 3D techniques as e.g., segmentation or outlining the periphery of a structure in all relevant 2D slices [68,91]. Volumetric analysis has also been applied in PMMR using segmentation to quantify the size of the hippocampus [92,93].

The 3D visualizations from PMCT serve as valuable complementary aid for visualizing fractures and foreign objects including metallic objects like projectiles, metal fragments, and gunshot pellets, and for visualizing their trajectories inside the body. Furthermore, whole-body PMCT scans can be processed to generate victim-specific 3D models, accurately reflecting the victim's proportions, which is useful for precisely pinpointing injury locations. Such models can then be employed to simulate possible ante mortem postures [38]. We have also conducted research on combining 3D models derived from CT scanning (representing internal structure) with those obtained through photogrammetry (capturing external details) [94–97].

3D models of bones acquired through both CT and MRI imaging methods find practical utility in biomechanical analysis. The application of Finite Element Analysis (FEA) provides an objective means to assess the likelihood of proposed traumatic events, offering a valuable tool for forensic pathologists when gauging the force or circumstances associated with an incident. Our exploration has involved evaluating the viability of subject-specific FEA in routine cases of blunt force skull fractures in five adults [98].

Furthermore, series of PMCT scans could be used to replicate chest compressions during cardiopulmonary resuscitation (CPR). Through multiple PMCT scans of a cadaver, time-resolved volumetric (4D) models could be generated [99]. This stands as a compelling instance of the "*hic gaudet mors succlirrere vitae*"-principle and example of how forensic imaging (here PMCT) might find utility in addressing clinical issues. Our involvement extends to diverse applications, including the calculation of body surface area [100] and the assessment of intracranial pressure [101].

Living age estimation in the juvenile

The estimation of living age in juveniles has been a recurring focal point of our research efforts. Through the utilization of diverse imaging modalities—such as CT, MRI, and X-rays—we have consistently explored the ossification status of various anatomical regions, e.g., the ossification of the clavicle [45,102], the hand [103,104] and the knee [86].

Furthermore, we have contributed to the field by providing reference samples for third molar development in a contemporary Danish context, along with prediction intervals. These efforts are reflected in studies by Larsen et al. [105], Arge et al. [106,107], and collaborative works such as Fiews et al. [108].

Forensic identification through gait analysis and stature estimation

Forensic identification through gait analysis and stature estimation has been a notable area of our research focus and a good example of how our research had influenced the examinations we offer to the Danish Police. Unfortunately, we do not offer gait analysis any longer due to limited number of cases and the challenge of maintaining expertise [41]. The first study on person identification by gait analysis was published in 2005 [44]. Subsequently, numerous studies have followed, encompassing a broad array of factors influencing gait analysis, including, e.g., velocity, head position [43,109–112]. We have also ventured into exploring other potential personal identification traits, such as facial features [113], and hand characteristics [114].

Forensic anthropology

Personal identification of skeletal remains, especially in scenarios where conventional identification methods are limited, can be achieved through forensic anthropological methods [115]. The advent of PMCT has led to the establishment of virtual skeletal collections. This development is of utmost importance, given the recognized variations among populations, secular trends, and the scarcity of skeletal collections. This virtual collection serves as a crucial resource for recalibrating existing methods and exploring novel ones [16].

Our research has explored how traditional age estimation methods, developed for dry bones, can be adapted for use on 3D virtual models [116,117]. Similar we did study for sex estimation [118]. Since CT scanning allows the exploration of not- visible features, we investigate the age-related changes of the trabecular bone for developing a new method [119]. We also used bony area such as part petrosa, not visible in a intact skull, to assess the sex [120,121]. Furthermore, we have calculate new formulas for height estimation from the femur, specifically tailored for application within the modern Danish population [122].

Future directions

It has been extensively demonstrated that PMCT serves as a valid screening tool during medico-legal external examinations, effectively aiding in the determination of the cause of death. However, in Denmark, its application in practice remains supplementary, and primarily used once the police already has requested a forensic autopsy.

We have initiated a national project aimed at integrating PMCT and rapid toxicological tests as additional tools within the framework of medico-legal external examinations. This strategic integration aims to offer a more comprehensive information package to law enforcement, empowering them to decide on the necessity of an autopsy. Currently, this decision relies solely on pre-existing information, including contextual details, medical records, witness statements, and medical opinions derived from external examinations. Unfortunately, only 10 % of cases proceed to forensic autopsy following medico-legal external examinations. Controversially, a circular from the Danish Ministry of Justice in 1970 mandates medico-legal autopsies and systematic toxicological analyses in cases where death is suspected to result from the abuse of illegal narcotics. However, numerous studies suggest that when deaths are attributed to drug toxicity, internal examinations as part of the autopsy rarely yield novel insights into the cause of death [123].

In the upcoming year, we anticipate acquiring more systematic knowledge through retrospective and prospective studies regarding the practical utility of PMCT and toxicology as diagnostic methods.

It is also important to remember that PMCT databases can also be used to address problems outside of forensic medicine. An example of this is the utilization of PMCT imaging and a 3D modeling approach to measure body surface area, which is an important parameter for medication dosage [100].

We will also continue our research into the integration of multiple imaging modalities. The combination of CT, MRI, and photogrammetry can offer a more comprehensive and multi-dimensional perspective on forensic cases, than any modality on its own. This approach has the potential to enhance our understanding of injuries, pathology, and potential causes of death with greater accuracy and nuance. Moreover, forensic imaging could gain a pivotal role in visualizing and reconstructing crime scenes. The creation of digital 3D reconstructions of crime scenes could provide valuable insights into the sequence of events leading to injuries or deaths. As a result, we are exploring the integration of additional visualization tools, such as virtual reality (VR) and simulation technologies, to enable jurors, judges, prosecutors, and defenders to immerse themselves in 3D reconstructions of forensic cases. This has the potential to assist in visualizing complex anatomical relationships and reconstructing crime scenes effectively.

Projects have also been initiated which explore some utilities provided by artificial intelligence (AI) and machine learning to forensic imaging. Automated image analysis tools have the potential to streamline segmentation processes, enhance the identification of patterns, and anomalies thus significantly augmenting the efficiency of forensic assessments. Achieving this would require close interdisciplinary collaboration with engineers and data scientists. Furthermore, to advance our capabilities, we should bolster our collaboration with radiologists and other medical experts. As medical imaging technology continues to evolve, we must also incorporate more advanced imaging techniques into our standard practices. This includes embracing breakthroughs in imaging techniques such as e.g., high-resolution- and spectral CT, micro-CT and MRI, improved MR-protocols (including spectral imaging protocols) for better soft and hard tissue contrast in clinical MRI systems. Such progress would likely facilitate novel (quantitative) imaging analyses which will gain increased emphasis for forensic interpretation compared to the current procedure, which is based solely on qualitatively reviewing the imaging data. In Denmark, the forensic imaging community is very much welcoming such developments and we strive to expand and improve forensic imaging services.

CRediT authorship contribution statement

Chiara Villa: Conceptualization, Writing – original draft, Writing – review & editing. **Sara Tangmose Larsen:** Conceptualization, Writing – review & editing. **Kasper Hansen:** Writing – review & editing. **Marianne Cathrine Rohde:** Writing – review & editing. **Martha Kirstine Haahr:** Writing – review & editing. **Lene Warner Thorup Boel:** Writing – review & editing. **Peter Mygind Leth:** Writing – review & editing. **Christina Jacobsen:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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