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Comparing the diagnostic accuracy of post-mortem CT with invasive autopsy in fire-related deaths: a systematic review

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ABSTRACT

Background: The value of post-mortem computed tomography (PMCT) in trauma victims is well established. In this review the diagnostic accuracy and value of PMCT will be investigated specifically for fire related deaths, which has yet to be fully investigated.

Methods: PRISMA guidelines informed this systematic review. A total of ten databases were searched in December 2020. All articles exploring the use of PMCT and autopsy to investigate fire related deaths in adults were deemed eligible for inclusion, and were reviewed by two independent researchers. The QUADAS-2 tool was used to assess the quality of these papers.

Results: Seven studies were selected, containing a total of 110 burns victims. PMCT was superior in identifying fractures, and is particularly accurate with regards to fractures and injuries of the skull, facial bones, neck and extremities. However, PMCT fared poorly in identifying signs of vitality during a fire compared to autopsy. Toxicological examinations to assess carbon monoxide levels were often still required to make a conclusive diagnosis of fire as the cause of death.

Conclusions: Despite the heterogeneity of the methodologies' reviewed, it is clear that PMCT is an extremely powerful visualisation tool with great potential for documentation and examination in forensic cases. The limitations of PMCT mean that it can not fully replace autopsy in these cases, but if autopsy is not available PMCT, in combination with a toxicology and histology examination, can identify the cause of death to a high degree of certainty.

Introduction

Burns may seem like a simple injury, but they are in fact a complicated pathology. They can cause destruction and mutilation of skin tissue, smoke-induced injuries to the airways, and postmortem diagnosis is often complicated by accompanying multi organ failure. Though it has been on a decline since the eighties, the number of fire related deaths in the United Kingdom (UK) is still prevalent, plateauing at between 200 and 300 hundred, per annum, in recent years [1]. The only discrepancies in the figures are in 2017 which was increased due to the Grenfell tower fire, and was reduced by 4% during the lockdowns incurred due to Covid-19 [1]. The most common cause of death in fire related incidents is neurogenic shock, also known as burn shock [2]. respiratory complications are also a major cause of early death, accounting for 34-45% of fire-related deaths, depending on the age of the person. Multi-organ failure is responsible for around 25% of all burn deaths, whilst sepsis accounts for around 14% [2].

Traditionally, invasive autopsy is the principal investigation of mortality and the main source of fatal injury data [3]. Forensic assessment of burned or charred bodies presents a unique challenge for pathologists due to the thermal damage inflicted on the tissues, which can make identification and examination extremely difficult, and presents an additional challenge in distinguishing between ante-mortem and post-mortem injury. The role of autopsy is to investigate the extensiveness of the damage, check for signs of vitality during the fire, and investigate the precise cause of death [4]. Like any other manual methodology, the value of autopsy is directly correlated to the diligence and care given to the procedure. The time taken and the experience of

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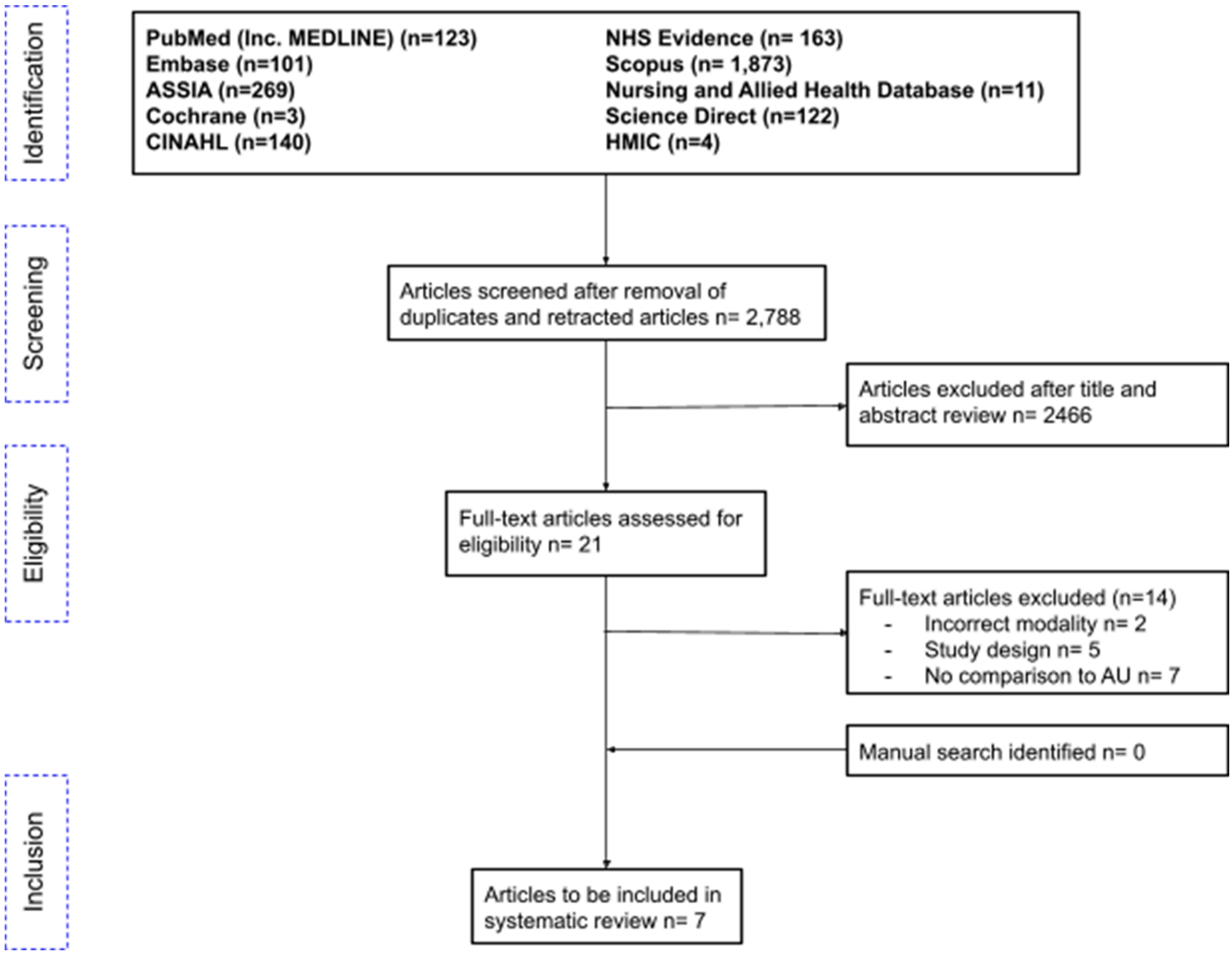

Fig. 1. PRISMA diagram of the database search.

the pathologist performing the autopsy play a significant role in the accuracy of the results [5].

There has been a global fall in autopsy rates over the last few decades [6], with public attitudes often being based on emotional or cultural considerations, and some faiths strongly opposing anatomical dissection [7]. Therefore the use of cross-sectional radiology to undertake post-mortem imaging can be very appealing to loved ones. When presented with the option between traditional autopsy and post-mortem imaging, the general public will overwhelmingly select imaging [8].

Post-mortem examinations have been augmented in recent years with the application of imaging techniques, and with the advances in radiological imaging the last few decades have shown a large leap towards minimally invasive autopsy (MIA) [9]. MIA allows fast internal examination and three dimensional reconstructions of a body, without destruction of tissue. Post mortem CT (PMCT) appears to be substantially better than autopsy among traumatic deaths, particularly in finding fractures and intervertebral injuries [6], in fire related deaths it is also able to very quickly detect many burn related pathologies, such as thermal fractures and, in more extreme cases, thermal amputation. It has been shown to be accurate with regard to size, shape and orientation of organs and foreign bodies, allow contamination free sampling, and allows investigation of anatomic regions that are not easily accessible by autopsy [9,10]. Digital images can also be stored indefinitely without degradation, a major advantage over invasive autopsy [11]. These factors have influenced a sharp increase in the UK of non-invasive post-mortem imaging [12].

A recent, large scale study compared the accuracy of PMCT with invasive autopsy in fire related deaths. The results demonstrate the promise of PMCT for fire-related deaths, with the radiologists being able to consistently detect soft tissue damage, gas collections and foreign bodies. Thermal injuries were also able to be detected on PMCT, that may otherwise have been missed at autopsy. Equally, however, some soft tissue injuries were detected during autopsy that were otherwise missed on imaging. These injuries held vital clues as to the cause of death and therefore the authors conclude that although there is great value in PMCT, it should be used in conjunction with autopsy [13]. The aim of this study is to investigate this finding further, by exploring all of the published literature comparing PMCT with autopsy in fire-related deaths.

Methods

This systematic review was performed in accordance with the PRISMA guidelines [14]. The method is demonstrated in Fig. 1. Ten databases, including PubMed, Scopus, and the Cochrane library (Fig. 1), were searched in December 2020. Four sets of search terms were used; the first focused on the population, limiting our search to those involved in fire-related deaths. The second defined the modality being investigated, this was restricted to only PMCT. The third was used to define an autopsy, used as a comparison. The fourth set defined the outcome, looking for examples including ‘cause of death’ and ‘diagnostic accuracy’ (Appendix A).

Table 1
Data extraction table.

Author Year Country	Journal	Study type	Design	No. of cases	Imaging protocol	Main findings	Conclusions
de Bakker 2019 The Netherlands	European Radiology	Retrospective Blind	PMCT vs AU total body	n= 50	CT = 32 or 64 slice. PACS.	PMCT was not useful in cases of CO poisoning, thermal airway damage or smothering, but did detect cause of death by trauma.	PMCT has value in forensic investigation of burned bodies in assessment of soft tissues, skeletal structures, and localisation of foreign bodies/gas collections. It cannot answer the main question of vitality during the fire, which can only be answered at autopsy. PMCT is a valuable add-on.
Levy 2009 USA	The American journal of forensic medicine and pathology	Retrospective	PMCT vs AU total body	n = 17 male adults	CT = 16 slice, 16 x 5mm collimation, pitch of 0.938:1, rotation speed of 0.5 seconds, and table speed of 18.75 mm/rotation	PMCT found intracranial haemorrhage not noted on autopsy, and a false positive for oral cavity material. Also noted lethal fractures and tissue lesions. Autopsy identified soot in the airways, and vascular and visceral injuries that had not been detected by CT.	MDCT can identify features of postmortem thermal injury in the majority of fire victims and demonstrate complex fractures. PMCT may serve as a useful pre-autopsy triage tool or provide additional anatomic information when the CoD is rendered by a limited autopsy.
Cittadini 2010 Italy	Medicine, science, and the law	Case Reports	PMCT vs AU total body	n=3	CT= 16 slice, 0.75mm slice collimation and width, 140kV, 160-180mAs, 15-24mm feed/rotation.	PMCT detected all CoD not related to the fires, but missed soot in airways. Did note congestion as a sign of vitality during fire.	PMCT is an important complement to autopsy procedures. It has potential in documentation and investigation of burned bodies.
Hueck 2020 Germany	European Journal of Radiology	Prospective, blinded, single centre, validation	PMCT vs reference standard AU total body	n= 3	CT= 128 slice, 120kV, 250 mAs, collumation 40mm, Pitch 0.984:1, matrix of 512x512. Slice 0.6mm. Soft tissue and osseous kernels. Rotation time 0.6s, scan time ~30s. + regions of interest scanned if required.	100% agreement between AU and CT for soft tissue and pulmonary edema. PMCT was only considered fair (67%) on epidural hematomas and signs of cardiac dysfunction. 100% agreement on CoD for burns/heat shock.	PMCT, complemented by toxicological and histological examination and information on circumstances of death, is sufficient to assess CoD in most cases, but should not be considered as an equivalent alternative.
Thali 2002 Switzerland	Journal of Forensic Science	Case Study	PMCT & MRI vs AU total body	n=1	CT= GE Lightspeed QX/i unit (4 slice) scanner, collimation 4x1.25mm; 950 axial cross sections. Coronal, sagittal & 3D reconstructions.	Showed heat epidural, fractures demonstrated well. Good for identifying foreign bodies and medical devices. CT showed vital reactions such as air embolism to the heart and blood aspiration to the lung. AU was able to show the pale colour of the organs, a sign of haemorrhage missed by CT.	Manner of death was not possible to determine radiologically. PM imaging is a good forensic visualisation tool with great potential for documentation and examination of charred bodies.
Cirielli 2018 Italy	Journal of Pathology Informatics	Prospective	PMCT vs reference standard AU full body	n=1	CT = 64 slice, pitch 1.173, running time 0.5s, length scout 1200cm, 120kV, slice thickness 2mm.	Dislocations and features seen at CT, but missed the severe skin bruises and burns. PMCT is not able to give a CoD.	Virtual autopsy may play a role as a screening test for traumatic deaths.
Kasahara 2012 Japan	Legal Medicine	Retrospective	PMCT vs AU	n=35	CT = 10mm slice thickness from the head to the pelvis. In cases with a suspicion of cervical spine injury, the neck was examined using a 2mm slice thickness.	All unable to be given even a suggestive CoD from imaging.	Inhalation burn or CO concentration in the blood is considered the only way to diagnose burn deaths. PMCT has no diagnostic value and provides no suggestive findings in burn victims.

The string of search terms was adjusted slightly to suit the functions of each database. A manual search of reference lists was also performed to ensure all relevant studies were included. Articles were initially screened by title and abstract, before a review of the full-text articles was undertaken to determine eligibility for inclusion.

All papers investigating fire related deaths in adults using PMCT and comparing this to autopsy were included. Any previous reviews were excluded. Case studies were deemed eligible for inclusion. These were then assessed for their quality and risk of bias. Two independent reviewers extracted and tabulated the data, and a descriptive summary of the data is included. Due to the heterogeneity of the study characteristics, a full meta-analysis was not possible. The resulting articles were assessed for quality using the QADRAS-2 tool by two independent reviewers.

Table 2
Comparison of pathologies found at CT and autopsy (n= no. found at CT, N= no. found at AU).

Area	Author	Injury details	CT	Autopsy	n/N
Skull/Facial bones	de Bakker	Skull/Facial bones injuries	24	21	1.14
	Levy	Cranial Injuries	12	12	1.00
		Facial bone injuries	4	4	1.00
	Cittadini	Skull fractures	1	1	1.00
		Facial bone injuries	1	1	1.00
	Thali	Loss of tabula externa	1	1	1.00
Intracranial	de Bakker	Heat Haematoma	11	11	1.00
	Levy	Intracranial Haemorrhage	9	12	0.75
	Cittadini	Extradural Haematoma	2	2	1.00
	Hueck	Heat Haematoma	2	3	0.66
	Thali	Heat Haematoma	1	1	1.00
Neck	de Bakker	Fracture / Dislocation	23	22	1.04
	Levy	Fracture / Dislocation	1	1	1.00
Thorax	de Bakker	Injuries inc. rib fractures	32	30	1.06
	Levy	Organ Laceration	0	7	0
	Cittadini	Multiple injuries, inc. rib fractures	3	3	1.00
	Hueck	Pulmonary oedema	3	3	1.00
		Cardiac Dysfunction	2	3	0.66
	Thali	Rib Fractures, lung contusion, blood aspiration	1	1	1.00
Abdomen	de Bakker	Organ injuries	34	41	0.82
	Levy	Organ Lacerations	0	17	0
	Cittadini	Bladder distension	1	1	1.00
	Thali	Intestinal protrusion & aortic collapse	1	1	1.00
		Severe exsanguination	0	1	0
Extremities	de Bakker	Upper Extremities	40	37	1.08
		Lower Extremities	36	36	1.00
	Levy	Fractures	15	15	1.00
	Cittadini	Fractures	1	1	1.00
	Thali	Fractures	1	1	1.00
	Cirelli	Fracture / Dislocations	2	1	2.00
Soft Tissues	de Bakker	Superficial skin changes	0	9	0
	Levy	Skin and Fat loss	16	16	1.00
	Hueck	Unspecified	3	3	1.00
	Cirelli	Severe skin bruising	0	1	0
Vital Signs	de Bakker	Soot aspiration	0	19	0
	Levy	Soot aspiration	0	2	0
	Cittadini	Soot	0	2	0
	Thali	Soot	0	1	0
	Kasahara	Soot/thermal airway damage	0	35	0
Cause of Death	de Bakker	Thermal Injuries	0	31	0
		Trauma	13 (missed smothering)	14	0.93
		Heart Failure	0	1	0
	Levy	Trauma	17	17	1
	Cittadini	Trauma	2	2	1
		Thermal Injuries	0	1	0
	Hueck	Thermal Injuries	3	3	1
	Thali	Trauma	1	1	1
	Cirielli	Thermal Injuries	0	1	0
	Kasahara	Thermal Injuries	0	35	0

Appendix B
Screening Tool.

Inclusion	Exclusion
Human population.	Non-human subjects.
Adults	Paediatrics.
Fire related deaths	Singular body part investigated
Post-mortem CT	Inappropriate imaging (i.e. MRI or X-ray)
Invasive Autopsy for comparison	No comparison with autopsy
Cause of Death	Identification outcome only
Diagnostic Accuracy	Review studies
Controlled studies/Comparative studies	

Results

Study selection

The PRISMA chart in Fig. 1 demonstrates the process of article selection. After removal of duplicates, the initial search retrieved 2788 articles, of which, 7 were deemed eligible for inclusion in this review. A summary of the included studies can be found in Table 2.

Study characteristics

One of the articles also investigated PMMRI, however this review is primarily focussed on PMCT and therefore the MRI findings were not included. All images were reported on by more than one person, which gives validity to their findings. However, only one article mentions the radiologist having post-mortem experience [15]. It is unclear how much training the pathologists have with regards to interpreting PMCT images, as only one article states that they had any training in this area [16].

One study focussed heavily on the use of 3D reconstructions, and sought to verify its reliability as part of a digital autopsy [16]. The custom built 3D virtual autopsy software could not identify CoD radiographically, however the autopsy did miss an ankle dislocation that was spotted due to the 3D reconstructions. Three studies report using both 2D and 3D reconstructions to give as much information as possible [13,15,17]. There were disparities in slice thickness, from 0.6mm to 10mm, and sample sizes, which ranged from a single case to 50 burns victims (Table 1).

All studies used conventional autopsy for comparison, however only two calculate sensitivity and specificity, both of these studies are larger studies that look at a variety of causes of death [16,18]. The other studies make direct comparisons with minimal statistical analysis Appendix B.

Quality assessment

All seven articles were deemed at low risk of patient selection bias and fared well in terms of index test applicability (Appendix C). All investigations were done in a timely manner with the PMCT conducted prior to autopsy. Blinding was unclear in four of the articles, with one study reporting that the autopsy was completed with prior knowledge of

Appendix C
QUADAS-2 quality assessment results.

Study	RISK OF BIAS PATIENT SELECTION	INDEX TEST	REFERENCE STANDARD	FLOW AND TIMING	APPLICABILITY CONCERNS PATIENT SELECTION	INDEX TEST	REFERENCE STANDARD
de Bakker et al.	☺	☺	☹	☺	☺	☺	☺
Cirelli et al.	☺	☺	☺	☺	☹	☺	☺
Thali et al.	☺	?	?	☺	☹	☺	☺
Cittadini et al.	☺	☺	?	☺	☺	☺	☺
Hueck et al.	☺	☺	☺	☺	☺	☺	☺
Levy et al.	☺	?	☺	☺	☹	☺	☺
Kasahara et al.	☺	?	?	☺	☺	☺	☹

☺Low Risk ☹High Risk ? Unclear Risk

the CT results. Two studies were of single cases, and there are applicability concerns with the reference standard of Kasahara et al. [19] study.

Pathologies by body area

Head

Burning effects of the head were seen in five of the studies, of which there are 38 skull injuries and 35 intracranial findings. One study had four cases with a completely missing cranium, and only four had a fully intact cranium [4]. Levy et al. [4] had three patients with intracranial haemorrhage that were missed on CT, contrasted to the perfect concordance of head injuries in the paper by Thali et al. [4]. One study insists that in one case PMCT alone could not determine whether the cause of death was burn or head injury [19]. One study found high variability in the detection of intracranial haemorrhages, as three of twelve cases were missed by PMCT but found on autopsy [4].

There are 44 skull and facial bone injuries in total, with varying degrees of severity. There are multiple cases in which the cranium was not whole [4], in seventeen of these the skull and intracranial structures were damaged. There is agreement between CT and autopsy in the findings of skull fractures in all papers that reported on them, however three cases of facial bone damage were missed at autopsy [13].

In total there were 35 heat haematomas discovered. In one case a heat haematoma was seen to extend beyond cranial structures, which is attributed to heat expansion. In all cases where part of the skull was missing, no heat haematoma was found. One study noted only a fair agreement between autopsy and PMCT when it came to epidural haematomas [18]. One heat haematoma found at autopsy had been missed by the PMCT. Herniation of the brain tissue was found in 16 cases, 5 of which also had heat haematoma, which was seen both on PMCT and autopsy [13]. Exposed brain tissue is also noted in the study by Levy et al. [4], but in this case the tissue is retracted and seared due to direct contact with flames.

Trauma caused subcutaneous oedema of facial tissues in two cases, seen on CT. Seven cases had complete destruction of the facial bones and tissues, and four had traumatic facial fractures. Other facial injuries include; soft tissue haematoma, nasal bone fracture, and severe congestion of the paranasal sinuses, which is an indication of respiratory activity during the fire [15]. Eight cases of thermal damage causing facial soft tissue loss, with two that had partial thermal destruction of the bone were discovered.

The Split Diploë Sign

The Split Diploë Sign is described as the splitting of the inner and outer table of the skull [13]. This is caused when the soft tissue covering of the skull is completely burned away, causing direct heat fractures to the skull. This phenomenon was observed in nineteen cases, including in some cases with only a partially intact cranium. This was shown in a second study, which used 3D reconstructions and a greater resolution to demonstrate the remaining portion of the Tabula externa, where the rest was burned away [17].

Neck

Two studies report neck injuries. Four out of these 24 cases were found to have a fractured spinal column on the CT. There is also one case with hyoid fractures detected at CT, and subsequent histology showed this was due to ante-mortem trauma, and not fire related [13].

Thorax

Six studies mention thorax damage. Autopsy failed to identify subcutaneous emphysema that was noted on PMCT in many cases. Other injuries noted on CT included: traumatic blood aspiration in the lungs and one case of haemothorax, which was identified on both autopsy and CT. Organ lacerations were a common injury to be missed by PMCT but were identified on autopsy.

There are four noted cases of pulmonary oedema, and pleural effusion was seen in 19 cases, 16 of which were determined to be hemorrhagic by the high attenuation on CT. One study observed haemothorax and pleural effusions at autopsy that allowed them to confirm the traumatic nature of these injuries [15]. In all cases, an autopsy was able to confirm the radiological findings.

The dense border sign is the name given to high attenuation of lung surface as a result of direct exposure to fire. This was on the CT of 17 cases with chest wall openings. Nine of the cases were found with pneumothorax and an intact thoracic wall, seen with CT [13]. A second article also found bilateral pneumothorax in one case, with associated lung collapse [15]. These findings were confirmed at autopsy.

One study found thermal damage to the heart in one case, and trauma damage to the heart in a second case. They also note that air was seen in the chambers in two cases [13]. This is in agreement with Thali et al. [4], who state that gas emboli were demonstrated well with imaging. Cardiac dysfunction was noted, but there is only 'fair' agreement between autopsy and CT in these cases [18]. One case of lacerations to the heart were missed on CT but picked up on autopsy. Fatal heart disease was revealed to be the cause of death in one case, but only after histological examination at autopsy.

Rib fractures were a common finding, some with callus formation. This could be irrelevant to the fire but may give further information about the patient. One study found multiple traumatic fractures and amputations within the thorax, with 9 severe amputations, including of the scapula, clavicles, and manubrium. Two cases of rib fractures were missed on autopsy [13].

Abdomen

Out of 62 total abdominal injuries, 36 were noted on CT. In one study alone, there were 34 cases of damage to the abdomen seen on CT, however autopsy revealed damage to internal organs in 7 more cases. One ruptured aorta and 9 cases of soft tissue defects had been missed on

PMCT [13]. The abdominal wall was completely destroyed by fire in 19 cases, but the internal organs were all well preserved. 12 subjects had abdominal organ damage, of which three had bowel damage exclusively. PMCT also showed 19 cases of air in the abdominal organs [13].

Protrusion of the intestines from the abdominal cavity, and gas embolism in the liver were found in one case, however the abdominal organs were relatively well preserved other than this. Autopsy did reveal that many organs were pale due to exsanguination, which is impossible to see on PMCT [17]. These findings are also mirrored in another paper, where 5 subjects had herniated intra-abdominal organs [4]. A distended bladder was observed in a single subject [15]. Autopsy and PMCT are in agreement over the soft tissue injuries to the abdominal wall found by Hueck et al. [18]. Traumatic injuries missed on CT included lacerations to the aorta, lung, liver, kidneys, spleen, bowel and bladder [4]. There is one case of dense border sign of the liver reported, where the organ was exposed to the fire. Levy et al. [4] also describe a similar sign attributed to 'searing' of the organs, and an associated decrease in organ size visible on PMCT.

Extremities

PMCT was able to identify burns in many cases. In one study upper extremities burns were seen in 40 subjects, and lower extremities in 36 subjects [13]. Of the upper extremities, 17 cases only the soft tissues were damaged, and burn associated fractures were seen in three cases. Thermal amputation was common, being seen in 20 cases of the upper and 15 of the lower extremities. Autopsy missed three cases of scapula damage that was noted on PMCT [13].

One study found that 100% of their cases had skin and subcutaneous fat loss, leading to muscle exposure. All but one of their cases showed signs of muscle retraction. Thermal cortical fractures were seen in 15 subjects, and thermal amputations were noted in 16. The degree and number of amputations was correlated with the extent of the charring. All extremity fracture findings correlated between CT and Autopsy in one study, and all amputations correlated bar one that was said to be thermal on CT but categorised as traumatic at autopsy [4].

Fractures were found in the extremities of many cases, and there was one case where a dislocation of an ankle was noted on PMCT, but missed at autopsy. In another case it was noted that the fractures were not heat shrunken, indicating that they are most likely traumatic in nature and could have been a source of air in the systemic circulation [17].

Fixed flexion in some cases made it impossible to scan the entire body in some cases due the position of the extremities and the size of the bore. Overall there were 32 cases with a pugilistic posture, two cases had arms fixed behind the back, and 2 had flexion deformities of the wrists and ankles only [4,13].

Foreign Body

Foreign bodies were a common incidental finding on PMCT. Some of the foreign bodies found included a nasogastric tube, cardiac wires, bullets, a stent, drug packages and an implantable cardiac defibrillator. CT also showed prostheses in the extremities of two cases [13]. One study did a thorough search for foreign bodies to aid in identification of the deceased, however only dental work was found [17].

One case was discovered with metallic staples and a metallic lighter head, which was easily discerned using 3D reconstruction, however the staples were missed at autopsy [15]. Metallic shrapnel was found in 7 cases, with associated track wounds that were seen on PMCT, however it failed to identify the cause of death in one of these cases, as a pericardial laceration that was only found at autopsy [4].

Projectile injury

One study identified one case that had incidental ballistics injuries, which had caused fragments of the cervical spine to be dislodged. They also found rib fractures due to the projectiles. Histology performed on autopsy found haematomas that confirmed this was an antemortem trauma injury [13].

Mottled lucencies

Two studies reported mottled lucencies on CT that were not seen at autopsy; these lucencies were attributed to direct fire exposure [4,13]

Soft tissues

The agreement between autopsy and CT regarding soft tissue injuries depends on their severity, for example skin bruises and superficial skin changes were found on autopsy that could not be seen on CT [13,16]. Two other studies found perfect agreement with regards to soft tissue injuries [4,18], however the extent of these injuries was much higher and included fat and muscle loss.

Vital reactions

Soot aspiration is a common vitality sign that is mentioned in all studies that were looking specifically at burns as a cause of death. De Bakker et al. (2019) found that autopsy was able to reveal soot and thermal damage in the airways in 19 cases. Two studies showed soot aspiration in the trachea and oesophagus, which was undetected on imaging [15,17], one of which was categorised as 'mild aspiration', which may be inconclusive as a vital sign.

One case where high attenuation particulate material was seen in the mouth and pharynx on imaging, which the authors suggested may be soot inhalation [4]. However, at autopsy there was no soot found, therefore leading to the conclusion that material must have been dirt or sand.

Toxicology and histology

Multiple studies describe the need for a toxicology and histology investigation as part of an autopsy in fire-related deaths. In one case of fatal heart disease was only discovered as the CoD after a histological examination [13]. Low carbon monoxide (CO) levels were found in two studies (ranging between 6 - 24%) [4,17], therefore it may be a contributing factor but not the main cause of death in those cases.

Only one study included alcohol levels in the toxicology reporting, including one case where a blood alcohol level of 5g/L was noted [15]. A second case had a high CO level of 85% showed definitive evidence of vitality during the fire.

Cause of death

Autopsy was found to be much more proficient in finding the cause of death. Nevertheless, de Bakker et al. [13] include 4 examples where autopsy was unable to determine the cause of death. Fire was described as the primary cause in 31 cases, with the remaining 15 cases attributed to ante-mortem trauma or organ disease. In the cases of CO intoxication, thermal damage to the airways or to smothering, PMCT had nothing to contribute with determining the cause of death. For the other cases, particularly those involving trauma, PMCT was only able to suggest a possible cause of death, but still required histology and toxicological investigation for certainty.

One study did find excellent concordance for the primary cause of death between autopsy and CT, however there was disagreement between a competing cause of death [18]. In another case of a fatal head injury, the burn injuries meant they could not say for certain what the primary cause was [4] (Table 2).

Discussion

PMCT is superior in identifying skull, facial bone, neck and extremity injuries, and provides excellent detailed information in these cases. However, it was found to be only fair when investigating intracranial and thorax injuries, and was inferior to conventional autopsy in diagnosing abdominal organ injuries, minor soft tissue injuries, vital reactions and cause of death (Table 2).

Current literature supports the finding that organ damage was commonly missed on PMCT [20], an option to increase sensitivity in this area is to introduce contrast enhanced studies. This is still relatively new to the field of forensics, and is not widely performed yet, therefore access can be limited. As the gold standard investigation for some pathologies, it would aid in identifying minor or superficial injuries, and improve the otherwise poor diagnosis of intra-abdominal organ injuries [21]. Further investigation into post-mortem contrast imaging, particularly in destructive injuries such as burns cases, would be valuable, as there is little literature on this subject currently.

The result is very different when looking at fractures, particularly of the extremities. These were uniformly found on CT, with many being missed by autopsy. This is not a surprising result as there is a vast amount of literature reporting PMCT as having a higher sensitivity than autopsy for skeletal injuries [22]. The advantage PMCT has, particularly when searching for skeletal injuries, is the ability to explore internal areas that are not routinely examined by the forensic pathologist [13]. One anatomical area that is often explored at autopsy is the thorax; rib fractures were more commonly identified on PMCT than at autopsy. In one case a hyoid bone was discovered to have been fractured on the PMCT, which led to subsequent autopsy investigations, and further specimen imaging. The histology performed at autopsy was able to diagnose the injury as being antemortem, highlighting that a collaboration between PMCT and autopsy was integral [13].

The protocols and procedures used to investigate these cases varied greatly. Since radiation dose is not a consideration in post-mortem scans, the only limitation to optimisation is the equipment available. The earliest study reviewed in 2002 used a 4-slice scanner, compared to the more recent studies that include up to a 128-slice scanner. Despite this difference in types of scanner, similar conclusions were reached regarding its function as an adjunct to autopsy.

Blinding could also have played a significant role in this data, and introduced an element of bias. Levy et al. [4] expressed that their lack of blinding, and use of a consensus for diagnosing injuries, was a major limitation in study design that may have influenced the interpretation of subtle findings. The non-blinding in one of the larger studies [13] could have significantly biassed the results of the autopsy, potentially leading to extra injuries being found, and skewing the data to make the sensitivity of PMCT appear lower than in actuality.

PMCT has the great advantage of being able to create three dimensional reconstructions; which were able to show, in detail, pathologies such as the displacement of a patella, caused by the surrounding ligaments and muscles being exposed to fire [13]. Tabula Externa loss was also clear, with two studies identifying this with 3D imaging and indicating it as a clear sign of thermal damage [4,17]

The degree of trauma and burning injuries are not consistently reported on or defined, which makes a meta-analysis impossible. It would be useful for future studies to have a uniform method of recording results such as the AIS or ISS scoring systems, which assign a numerical value to the severity of the injuries, allowing for direct comparison.

Multiple metallic projectiles were discovered by PMCT in one study, and a histological examination performed at autopsy found haematomas that confirmed the antemortem nature of these injuries [13]. Current literature suggests that PMCT is better at finding the fragments, and can show the wound tracking, however autopsy is able to localise gunshot injuries better [23]. There may be discrepancies in these cases due to the thermal destruction of tissues, which may make identifying bullet wounds more difficult.

An advantage of PMCT reported by a number of the studies is that gas emboli are easily recognisable, and can be missed on autopsy. Gas release may be due to retraction of blood products or formation of coagulum as a result of thermal effects, however they can also be caused by traumatic fractures [17]. Gas collections were also found within marrow spaces where flames had direct contact with bones, and were noted on PMCT scans as mottled lucencies. Thali et al. [4] talk extensively about gaseous changes seen on imaging, but do not specify whether this is on CT or MRI, which could be misleading. Gas accumulations are much easier to see on PMCT, however according to current literature it is difficult to tell the origins, and whether the gas is putrefactive or traumatic [24].

The number of burn victims varied between each study, Kasahara et al. [19] had the largest number of cases at 35. This was a not insignificant number and would have added much value to our study, however they did not report their PMCT findings in these cases, instead dismissing them as undiagnosable due to PMCT being unable to establish vitality or carbon monoxide concentrations. This means that no further data can be obtained, and these cases were not able to be added to the collective results table. The study has been included for completeness.

The patient selection was also extremely variable. One article had significant bias in this area due to all cases being submitted to extreme trauma. This meant an irregularly high rate of injuries in each case [4], and due to this smaller injuries were more likely to be overlooked. All causes of death in this study were attributed to trauma at both PMCT and autopsy, with the fire being incidental. There are further discrepancies between the studies with regards to reporting the causes of death, with some studies indicating that diagnosing this by PMCT alone was impossible. The most notable outcome of this review is that PMCT was able to identify when trauma was a cause of death, but seemed to be less accurate in diagnosing thermal injuries. The usefulness of PMCT for traumatic deaths is widely reported, it can demonstrate major injuries and can disclose most primary or competing causes of death [22]. The difficulty is in discovering whether these injuries were ante or post mortem, and whether they were a result of thermal application or trauma. There is some investigation into the shrinkage of bones that have been in fire [25], however further research into what effect fire has on musculoskeletal tissue could help make these image interpretations easier.

Uniformly, vital signs were missed by PMCT. The vital signs described included thermal damage and soot in the airway, in combination with CO intoxication. The toxicological examinations included within a standard autopsy were a conclusive indicator of CO poisoning, and allowed for confirming cause of death to a high degree of certainty. PMCT was able to identify some vital reactions, such as mucosal congestion of the paranasal sinuses and peribronchovascular oedema, which indicate inhalation during the fire, but these findings require confirmation at autopsy [15]. The inability to see most common vital signs has led to studies dismissing PMCT as a method of discovering cause of death by thermal injuries, and in turn has led to a poorer amount of information regarding what signs are visible. The importance of toxicology and histology reports is clear, with one histological report identifying a case of heart failure that might otherwise have been missed, and CO levels being a definitive sign of smoke inhalation. Therefore, for every fire related death, a toxicology and histology report should be completed alongside any postmortem investigations.

There is little literature on who should interpret PMCT images. A pathologist often knows which findings are important to establish the cause of death, but does not usually have a radiological background, whereas a radiologist can interpret images but may not understand what are considered normal post mortem changes [22]. One article found that radiologists often find more injuries, particularly if they are skeletal, whereas pathologists detect more organ and soft tissue injuries [26]. The conclusion is that for the optimal outcome both a radiologist and pathologist should be involved in the diagnosis, and of the included studies only two had this approach [15,19]. It is worth noting that there is an increasing number of radiologists that are specialising in the field of forensics, who are likely to be the most suitable candidates to interpret post mortem images. Future research is required to understand the impact of this change.

A systematic approach using the PRISMA guidelines was undertaken to ensure the strength and replicability of this study. Prior to submitting this paper, a final search was done to avoid missing any new publications. The search was conducted in the same way but only included December 2020 to December 2021. After reviewing the titles and abstracts of 105 additional search results, one further article was discovered that may have been of importance, however on closer inspection there were no autopsy results published and therefore the data could not be added [27].

This study is also restricted by only investigating PMCT as a source of imaging. PMMRI is newer to forensic imaging, but the high soft tissue resolution can make it particularly useful in investigating natural causes of death and traumatic soft tissue injuries. One area PMMRI excels in is the visualisation of pathologies of the abdominal organs, in comparison this review found PMCT to be weak in this area. Studies that compare PMMRI and PMCT for trauma victims conclude that organ injuries are not better visualised on MRI, but it does perform better for soft tissue diagnostics [20].

Another limitation of this review is that no meta-analysis could be completed. The disparity between the methods and the results was too great. Instead a quotient was found that gave simple numerical values that could be compared. These quotients were able to show obvious trends and anomalous results, which enabled discussion. Unfortunately, this review only found seven articles that compared PMCT and autopsy in fire related deaths, and of these seven articles the largest population was 50. A larger scale study is recommended.

Conclusion

Despite its many advantages, this study has demonstrated that PMCT is less accurate with regards to two of the most important questions when examining a burns victim; determining vitality during the fire and the overall cause of death. There are some indications of vitality that PMCT does show, such as mucosal congestion of the paranasal sinuses and peribronchovascular oedema, which can then be confirmed with invasive autopsy. However, without a toxicology report there is little possibility of PMCT being able to give a definitive cause of death. The role PMCT has to play in the post mortem diagnosis will depend on the specific questions that require answering, and may be determined on a case by case basis. Overall the most complete examination will be derived from a combination of conventional autopsy and PMCT, and this is therefore recommended as the gold standard.

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Declaration of Competing Interest

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Appendix A. Search Syntax

The first search term focuses on the population, limiting our search to those involved in fire-related deaths. The second defined what imaging would be searched for, to keep this study specific, this was restricted to just PMCT. The third was used to define an autopsy, used as a comparison, and finally the outcome was included, looking for examples including 'cause of death' and 'diagnostic accuracy'.

Boolean operators were utilised as they are ideal for conducting database searches. The keywords identified in the PICO table and all possible alternative terms, synonyms and alternative spellings are included to increase sensitivity (Offredy & Vickers, 2010).

The Syntax used for this study is as follows:

(Burn OR Fire OR Cremated OR Charred) AND (CT OR Computed Tomography OR PMCT OR "Post mortem computed tomography" OR Virtopsy OR Digital Autopsy) AND (Post mortem OR Autopsy OR Forensic OR Necropsy) AND (Diagnos* OR Accuracy OR "Cause of Death" OR Injur*)*

ScienceDirect has a strict use of only 8 boolean operators per field, and does not allow for 'wild cards'. A simplified search was devised, and was used for this database only. The syntax for this is as follows:

(fire OR burn) AND (PMCT OR "Post-mortem Computed tomography") AND autopsy AND (accuracy OR injuries OR death).

The databases found through Ovid could not have a syntax that included quotation marks, therefore these were left out of those searches.

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