Forensic Sci Med Pathol (2017) 13:284–292
DOI 10.1007/s12024-017-9878-1

ORIGINAL ARTICLE

Accuracy of non-contrast PMCT for determining cause of death

Garyfalia Ampanozi[1] · **Yannick A. Thali**[1,2] · **Wolf Schweitzer**[1] · **Gary M. Hatch**[3] · **Lars C. Ebert**[1] · **Michael J. Thali**[1] · **Thomas D. Ruder**[1,4]

Accepted: 1 May 2017 / Published online: 15 June 2017

Abstract The aim of this study was (1) to compare levels of accuracy regarding the categorization of causes of death between non-contrast post-mortem computed tomography (PMCT) and the final forensic report as well as between autopsy and the final forensic report, and (2) to assess levels of confidence regarding the categorization of causes of death after non-contrast PMCT and after autopsy. This prospective study was conducted over a 5 month period during which 221 cases were admitted to our institute for forensic investigations. Whole-body PMCT and forensic autopsy were performed in every case. Of these, 101 cases were included in the final study population. Inclusion criteria were: (1) age > 18 years, (2) presence of at least one of the two principal investigators at the time of admission. One radiologist and one forensic pathologist independently read all PMCT datasets using a report template. Cause of death category and confidence levels were determined by consensus. Forensic autopsy was performed by two forensic pathologists; both unblinded to imaging results. Both post-imaging and post-autopsy cause of death categorization were compared against the final cause of death, as stated in the forensic expert report, which included findings from histology and/or toxicology. Accuracy of post-imaging cause of death categorization in reference to the final cause of death category was substantial (82%, 83/101 cases, Kappa 0.752). Accuracy of post-autopsy cause of death categorization in reference to the final cause of death category was near perfect (89%, 90/101 cases, Kappa 0.852). Post-imaging sensitivity and specificity regarding the categorization of causes of death were 82% and 97%, respectively. Post-autopsy sensitivity and specificity regarding the categorization of causes of death were 89% and 98%, respectively. There was a high consistency between the accuracy of post-imaging cause of death categorization and post-imaging levels of confidence. There was less consistency between accuracy of post-autopsy cause of death categorization and post-autopsy levels of confidence. In this study categorization of causes of death based on non-contrast enhanced PMCT alone, and on PMCT and macroscopic autopsy together, proved to be consistent with the final cause of death-category as determined based on all available information including PMCT, autopsy, and (if available) histology and/or toxicology in more than 82% and 89% of all cases, respectively. There was higher consistency between levels of confidence and accuracy of causes of death categorization was higher post-imaging than post-autopsy. These results underline the fact that the diagnostic potential of PMCT goes beyond the assessment of trauma cases.

✉ Thomas D. Ruder
thomas.ruder@irm.uzh.ch; thomas_ruder@hotmail.com

1 Institute of Forensic Medicine, Department of Forensic Medicine and Imaging, University of Zurich, Winterthurerstrasse 190/52, CH-8057 Zurich, Switzerland

2 Institute of Radiology, Cantonal Hospital Lucerne, CH-6000 Lucerne, Switzerland

3 Radiology-Pathology Center for Forensic Imaging, Departments of Radiology and Pathology, University of New Mexico School of Medicine, Albuquerque, NM 87102, USA

4 Institute of Diagnostic, Interventional, and Pediatric Radiology, University Hospital Bern, University of Bern, CH-3010 Bern, Switzerland

Keywords Forensic radiology · Post-mortem computed tomography · PMCT · Cause of death

Introduction

Post-mortem cross-sectional imaging, notably post-mortem computed tomography (PMCT), is routinely used in forensic death investigations in many forensic institutes across the world [1, 2]. PMCT is often used as adjunct to autopsy, but its role varies, depending on local habits and traditions, applicable law, access to scanners, availability of experts, financial resources, and case circumstances [3–5].

There is general agreement that PMCT is superior to autopsy regarding the detection of fractures, gas collections, and foreign bodies, whereas autopsy is superior to non-contrast enhanced PMCT regarding the detection of soft tissue and organ pathologies [6–14]. The reported accuracy of post-mortem imaging in diagnosing the cause of death ranges from 6% to 70% [3, 6, 7, 10, 11, 15–17]. This wide range of accuracy can be traced back to methodological differences between these earlier studies regarding rater experience with PMCT, composition of study populations, definition of the gold standard against which PMCT is compared, and categorization of causes of death [6–12].

In the past, many researches had to rely on inexperienced raters, such as radiologists with no or minimal experience in post-mortem imaging [6, 8, 10, 11, 18–20] or on raters with no formal training in radiology (i.e. usually forensic pathologists) [3, 7, 21]. This approach is – figuratively speaking – comparable to assessing the diagnostic potential of forensic autopsy by relying on clinical pathologists with no experience in forensic pathology or on investigators with no formal training in forensic pathology (e.g. radiologists). In recent years however, experience with PMCT has grown through an increasing use of PMCT in routine case work and through research. Today, investigators have access to a larger body of literature on non-traumatic PMCT findings than their forerunners, describing signs related to related to heart failure [22–24], aortic dissection [25], pulmonary embolism, [26, 27], intoxication [28, 29], or hypothermia [30, 31]. The availability of these new sources enables forensic radiology to follow the example of clinical radiology and gradually move away from free-text reporting to reporting with templates [32]. Report templates have proved to increase the quality of radiology reports by acting as systematic guide through all pertinent findings of a radiologic study and thus counterbalance negative effects such as rater inexperience or bias [33–35].

In view of the growing experience with PMCT, growing body of literature on PMCT, and developments in structuring radiology reports, we considered it necessary to re-evaluate the accuracy of PMCT in diagnosing cause of death.

The aims of this study were (1) to assess the accuracy of non-contrast PMCT and of autopsy regarding the categorization of the cause of death category (in reference the final forensic report), and (2) to assess levels of confidence regarding the categorization of causes of death after non-contrast PMCT and after autopsy.

Materials and methods

This prospective study was conducted at the Institute of Forensic Medicine, University of Zurich, Switzerland, over a 5 month period. Ethical approval was waived by the ethics committee (Ethics Committee of the Canton of Zurich) (Number KEK ZH-Nr. 15-0686).

During the study period, 221 cases were admitted to the institute for forensic investigations. Routine whole-body PMCT and forensic autopsy was performed in every case. Inclusion criteria were: (1) age > 18 years, (2) presence of at least one of the two principal investigators at the time of admission. A total of 101 cases (68 males, 33 females; mean age 57 ± 18 years; age range 21–92 years) were included in the final study population.

PMCT

Prior to autopsy, PMCT was performed on a 128-slice dual source CT scanner (Flash Definition, Siemens Healthineers, Erlangen, Germany). The scan parameters used were as follows (adapted from [36]): tube voltage 120 kVp; variable mAs values (reference 280 mAs) using automatic dose modulation software (CARE dose 4D, Siemens Healthineers, Erlangen, Germany) for whole-body scan and 450 mAs for head scan; 128 × 0.6 mm slice collimation; rotation 0.6 s; pitch 0.6; slice thickness 1 mm (0.75 mm for the head); increment 0.5 mm (0.6 mm for the head). Images were reconstructed with both soft tissue and bone kernels.

Autopsy

Forensic autopsy was performed by one forensic pathologist and one forensic pathologist in training. Autopsy included opening of all three body cavities (cranial, thoracic, and abdominal) and dissection of all organs in every case. Autopsy protocols were dictated or typed conforming to a structured report template.

Note: following standard operating procedure at our institution ancillary examinations such as histology and/or toxicology were only conducted if the forensic pathologists considered them necessary based on the case circumstances, imaging findings, and autopsy results. In total, histology was requested in 49/101 and toxicology in 56/101 cases.

Post-imaging cause of death

One radiologist and one forensic pathologist (both with three years of full-time experience in reading PMCT) independently read all PMCT datasets using a report template with a checklist of 110 individual potential findings which had to be assessed in each case. The template was adapted from the report template used at our institute for reporting of PMCT.

Both positive and negative findings were recorded in the check-list. After completing their report, PMCT raters were required to state what they considered to be the cause of death based on organ-system oriented categories (see below). A four point Likert-scale was used to indicate their level of confidence (4 = certain; 3 = probable; 3 = possible; 1 = uncertain) (adapted from [10]). The PMCT raters repeatedly convened in consensus meetings to compare completed report templates and diagnosis of causes of death (in batches of 5 to 10 cases), review and record discrepant findings, and settle on a consensus for the cause of death-category and level of confidence. To facilitate readability this consensus cause of death-category and consensus level of confidence as determined after imaging will be referred to as *post-imaging cause of death-category* and *post-imaging level of confidence* in subsequent paragraphs, figures, and tables. Note: PMCT raters were aware of the essential case circumstances when reading the PMCT images. PMCT raters were blinded to any other case relevant information, including all findings acquired during the time interval between the initial PMCT read-out and the consensus meeting.

Post-autopsy cause of death

A similar consensus approach was also used by the two forensic pathologists. During autopsy they would freely discuss all morphologic findings and before concluding the procedure, they would review all autopsy findings and settle on a consensus for the cause of death-category and consensus level of confidence. It is important to note that the forensic pathologists were aware of both the circumstances of death and PMCT findings (except for the radiologic categorization of the cause of death) prior to and during autopsy. Accordingly, the pathologists' categorization of the cause of death was always based on both, PMCT findings and autopsy findings. To facilitate readability the consensus cause of death-category and consensus level of confidence as determined after autopsy will be referred to as *post-autopsy cause of death-category* and *post-autopsy level of confidence* in subsequent paragraphs, figures, and tables.

Final cause of death

Both post-imaging and post-autopsy cause of death categorization was compared against the final cause of death-category. This *final cause of death-category* was formulated by the forensic pathologists upon completion of all forensic investigations and is based on all available information including case circumstances, findings from the scene, from post-mortem imaging, from autopsy, and (if available) from histology and/or toxicology.

Definition of cause of death for this study

For this study, causes of death were categorized according to the assumed primary organ (or organ system) responsible for causing death. The use of organ-based causes of death was adopted from earlier forensic studies by Roberts et al. and Leth et al. [10, 11]. Causes of death were classified into the following categories of organs and organ systems (adapted from [10]): 1) heart, coronary arteries, and pulmonary arteries (HCP); 2) central nervous system (CNS); 3) aorta and peripheral arteries (APA); 4) respiratory (RES); 5) metabolic (MET), 6) gastrointestinal (GIT); 7) multisystem disorder (MSD); 8) undetermined (UDT). Although this approach does not comply with WHO or medical examiner's recommendations on formulating a cause of death (primary cause, secondary cause, underlying pathology) [37, 38], it was used in this study to facilitate statistical analysis of the results. Benefits and limitations of this approach are reviewed in the Discussion section.

Statistical analysis

Statistical analysis of the data was performed with IBM® SPSS® Statistics (Version 20 release 20.0.0, 2011, IBM Corp. Armonk, NY, USA). In addition Excel (Microsoft Excel, 2010 Microsoft Corporation, Redmond, WA, USA) was also used for creating graphs of study data. Categorical variables were described as percentages of the total. Accuracy of post-imaging as well as post-autopsy cause of death-categories was calculated in relation to the final cause of death-category. Levels of concordance between post-imaging, post-autopsy, and final cause of death-categories were assessed with Cohen's Kappa statistic. Concordance was classified as slight (0.01 to 0.20), fair (0.21 to 0.40), moderate (0.41 to 0.60), substantial (0.61 to 0.80) and almost perfect (0.80 to 1.00) according to [39]. Sensitivity and specificity were calculated for post-imaging and for post-autopsy cause of death-categories.

Results

Categories of causes of death

Post-imaging causes of death were categorized as follows: HCP 44.6% (45/101), CNS 28.7% (30/101), APA 9.9% (10/101), RES 1.0% (1/101), MET 5.9% (6/101), GIT 1.0% (1/101); MSD 5.0% (5/101), and UDT 3.0% (3/101).

Post-autopsy causes of death were categorized as follows: HCP 35.6% (36/101), CNS 32.7% (33/101), APA 10.9% (11/101), RES 4.0% (4/101), MET 1.0% (1/101), GIT 4.0% (4/101); MSD 5.9% (6/101), and UDT 5.9% (6/101).

Final causes of death were categorized as follows: HCP 36.6% (37/101); CNS 34.7% (35/101); APA 10.9%

(11/101); RES 1.0% (1/101); MET 1.0% (1/101); GIT 4.0% (4/101); MSD 8.9% (9/101), and UDT 3.0% (3/101). See Fig. 1 for details.

Accuracy of post-imaging and post-autopsy causes of death categorization

Accuracy of post-imaging categorization of causes of death in reference to the final cause of death-category was substantial (82%, 83/101 cases, Kappa 0.752). Accuracy of post-autopsy categorization of causes of death in reference to the final cause of death-category was near perfect (89%, 90/101 cases, Kappa 0.852). In 80/101 cases (79%) the cause of death had been correctly categorized post-imaging as well as post-autopsy. This means that in 3/83 cases, the cause of death was correctly categorized post-imaging, but was incorrectly categorized post-autopsy (cognizant of PMCT findings) whereas in 10/90 cases, the cause of death was incorrectly categorized post-imaging, but was correctly categorized post-autopsy. In 8/101 cases both imaging and autopsy failed to correctly categorize the cause of death. In these 8 cases the final category of cause of death was established through histological (7/8 cases) and toxicological analysis (1/8 cases), respectively. See Fig. 2 for details.

Sensitivity and specificity of post-imaging and post-autopsy causes of death categorization

Note: cause of death-categories with a sample size of $n < 10$ (i.e. RES, MET, GIT, MSD, and UDT) were not calculated individually, but instead calculated as one category, labelled miscellaneous (MSC).

Post-imaging sensitivity and specificity regarding the categorization of causes of death were 82% and 97%, respectively. Highest sensitivity was achieved for HCP at 92% (at the cost of the lowest specificity at 83%); highest specificity was achieved for APA and CNS at 100% for both categories (sensitivity for APA 91%, sensitivity for CNS 86%). Lowest sensitivity was found for miscellaneous at 50% (i.e. pooled sensitivity of RES, MET, GIT, MSD, and UDT).

Post-autopsy sensitivity and specificity regarding the categorization of causes of death were 89% and 98%, respectively. Highest sensitivity and specificity was achieved for APA with 100% sensitivity and 100% specificity. Lowest specificity was found for HCP at 95%. Lowest sensitivity was also found for miscellaneous (MSC) at 78%. See Table 1 for details.

Levels of confidence of post-imaging and post-autopsy causes of death categorization

Post-imaging confidence levels regarding cause of death categorization were: 26% certain (26/101); 40% probable (40/101); 18% possible (18/101), and 17% uncertain (17/101). There was a high consistency between post-imaging levels of confidence and the accuracy of post-imaging cause of death categorization: cause of death certain (26/101): accuracy 100% (26/26); cause of death probable (40/101): accuracy 83% (33/40); cause of death possible (18/101): accuracy 72% (13/18); cause of death uncertain (17/101): accuracy 65% (11/17 cases).

Post-autopsy confidence levels regarding cause of death categorization were: 51% certain (51/101); 29% probable (29/101); 13% possible (13/101); and 8% uncertain (8/101). There was less consistency between post-autopsy levels of confidence and the accuracy of post-autopsy causes of death categorization: cause of death certain (51/101): accuracy 98% (50/51); cause of death probable (29/101): accuracy 83% (24/29); cause of death possible (13/101): accuracy 100% (13/13); cause of death uncertain (8/101): accuracy 38% (3/8). See Table 2 and Figs. 3 and 4 for details.

Discussion

In this study categorization of causes of death based on non-contrast enhanced PMCT alone, and on PMCT and macroscopic autopsy together, proved to be consistent with the final

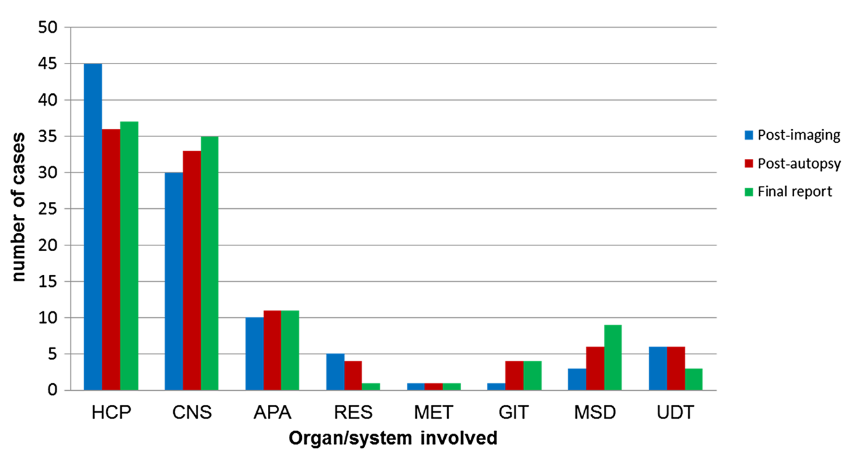


Fig. 1 Bar-chart comparing post-imaging categories of causes of death (*blue bars*) and post-autopsy categories of causes of death (*red bars*) to categories of the final causes of death (*green bars*)

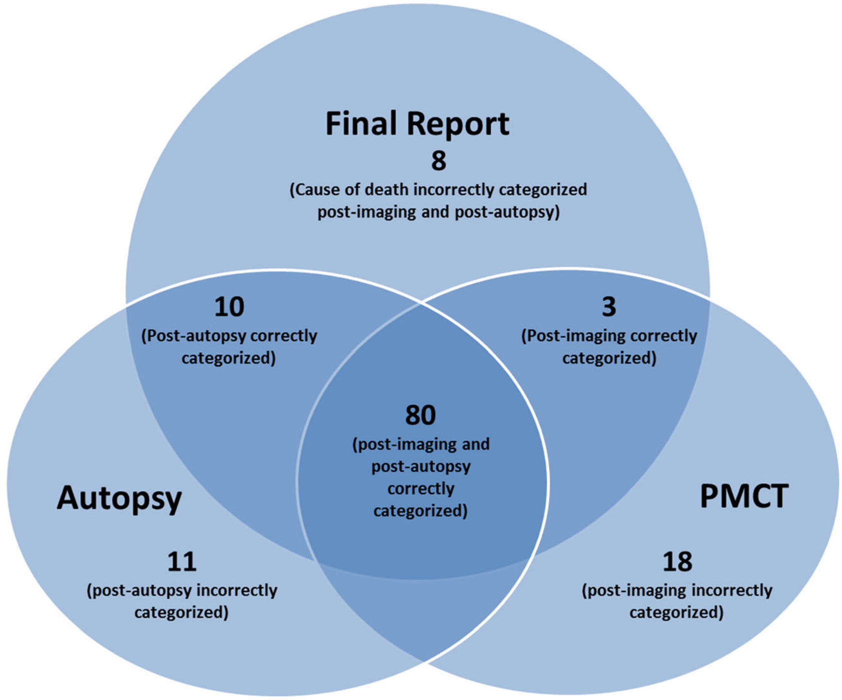


Fig. 2 Overview of the accuracy of post-imaging and post-autopsy categories of causes of death in comparison to the final cause of death. In 8 cases, both post-imaging and post-autopsy failed to correctly categorize the cause of death. The final cause of death was established by histology (7 cases) and toxicology (1 case)

cause of death-category as determined based on all available information including PMCT, autopsy, and (if available) histology and/or toxicology in more than 82% and 89% of all cases, respectively.

Mean accuracy of post-imaging cause of death categorization was only was only 7% lower than mean accuracy of post-autopsy cause of death categorization. Overall, rater levels of confidence regarding causes of death categorization were lower post-imaging than post-autopsy, but consistency between levels of confidence and accuracy of causes of death categorization was higher post-imaging than post-autopsy.

The fact that the accuracy of post-imaging cause of death-categories was 82% in reference to the final cause of death-category strongly indicates that diagnostic potential of PMCT is widely underestimated in the existing literature (published range of diagnostic accuracy 6%–70%) [3, 6, 7, 10, 11, 15–17]. This discrepancy between the published literature and the current study is primarily caused by four (partially cumulative) factors: 1) PMCT raters in this study were experienced with forensic and postmortem imaging; 2) a larger body of published literature on PMCT was available to raters in this study than to raters in prior studies [3, 6, 7, 10, 11, 15–17]; 3) PMCT findings were reported with structured report templates [3, 6, 7, 10, 11, 15–17]; and 4) causes of death diagnoses were categorized in to organ/organ-system oriented categories [10, 11].

Rater experience is a crucial factor for high diagnostic accuracy. Both PMCT raters in this study had been exposed to PMCT images (for reporting and research) on a daily basis for several years before participating in this study. Not all of the above cited studies [3, 6, 7, 10, 11, 15–17] disclose their raters' experience, but in many cases raters had no experience with PMCT or no training in radiology at the outset of the study. The field of forensic radiology has grown rapidly over the past decades and new insights into the diagnostic potential of PMCT (notably outside the realm of trauma-related findings) are published at an astonishing rate [1]. This means that in addition to their practical experience, raters in this study

Table 1 Sensitivity and specificity of post-imaging and post-autopsy categories of causes of death in comparison to the final cause of death. Note: cause of death-categories with a sample size of $n < 10$ (i.e. RES, MET, GIT, MSD, and UDT) were not calculated individually

Cause of death categories	Post-imaging		Post-autopsy	
	Sensitivity	Specificity	Sensitivity	Specificity
HCP	92%	83%	89%	95%
CNS	86%	100%	91%	98%
APA	91%	100%	100%	100%
Miscellaneous* (RES, MET, GIT, MSD, UDT)	50%	98%	78%	99%
Overall	82%	97%	89%	98%

Table 2 Overview of levels of confidence and diagnostic accuracy of post-imaging and post-autopsy categories of causes of death in comparison to the final categories of causes of death. Correct categorizations are listed as *true*, incorrect categorizations as *false*

Category	Likert	Post imaging			Post autopsy			final
		Total	*True*	*False*	Total	*True*	*False*	
HCP	certain	3	*3*	*0*	19	*18*	*1*	
	probable	23	*18*	*5*	14	*12*	*2*	
	possible	13	*10*	*3*	3	*3*	*0*	
	uncertain	6	*3*	*3*	0	*0*	*0*	
	∑	45	*34*	*11*	36	*33*	*3*	37
CNS	certain	16	*16*	*0*	18	*18*	*0*	
	probable	8	*8*	*0*	7	*7*	*0*	
	possible	3	*3*	*0*	7	*7*	*0*	
	uncertain	3	*3*	*0*	1	*0*	*1*	
	∑	30	*30*	*0*	33	*32*	*1*	35
APA	certain	7	*7*	*0*	7	*7*	*0*	
	probable	3	*3*	*0*	2	*2*	*0*	
	possible	0	*0*	*0*	2	*2*	*0*	
	uncertain	0	*0*	*0*	0	*0*	*0*	
	∑	10	*10*	*0*	11	*11*	*0*	11
MSC	certain	0	*0*	*0*	7	*7*	*0*	
	probable	6	*4*	*2*	6	*3*	*3*	
	possible	2	*0*	*2*	1	*1*	*0*	
	uncertain	8	*5*	*3*	7	*3*	*4*	
	∑	16	*9*	*7*	21	*14*	*7*	18
Overall	certain	26	*26*	*0*	51	*50*	*1*	
	probable	40	*33*	*7*	29	*24*	*5*	
	possible	18	*13*	*5*	13	*13*	*0*	
	uncertain	17	*11*	*6*	8	*3*	*5*	
	∑	101	*83*	*18*	101	*90*	*11*	101

also had access to a larger body of literature on PMCT than their predecessors. This has allowed for the design of structured report templates with evidence-based, forensically relevant PMCT criteria beyond the assessment of traumatic injuries [22–31]. While the use of a report template is generally considered to increase diagnostic accuracy compared to free-text reports [33–35], it is difficult to gauge the benefit of using report templets in this study because the majority of the previously published articles on diagnostic accuracy of PMCT do not comment on the report structure used for reporting. The only hint that previous studies have used free-text reports rather than report templates lies in the observation that use of report templates is never mentioned and that free-text reporting is still widely used in radiology.

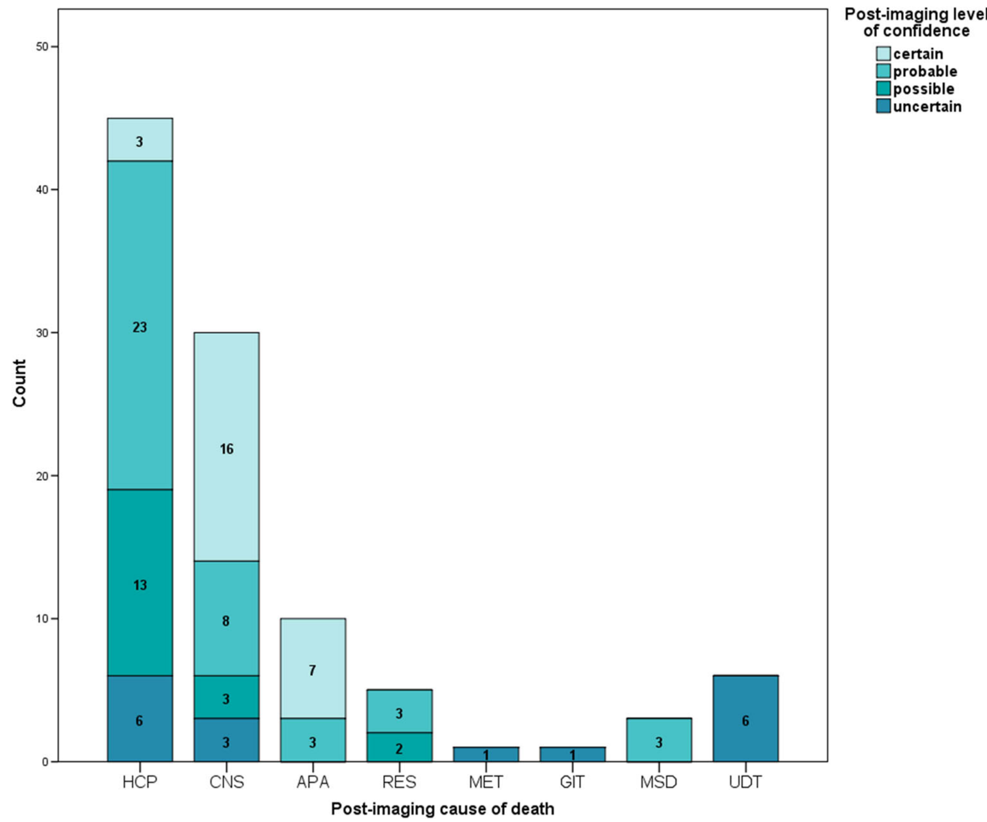
In this study, there was a high consistency between post-imaging levels of confidence and the accuracy of post-imaging causes of death categorization. Although raters felt certain about the cause of death-categories in only a quarter of all cases (25.7%, 26/101 cases), in *all these cases*, their categorization was correct. In other words, in all cases where PMCT raters were certain about their categorization of a cause of death, subsequent autopsy, histology and/or toxicology confirmed the post-imaging cause of death-category in all cases in this study. This result differs from the findings in the study by Roberts et al., where raters felt certain about half (48%, 88/182 cases [10]) of the post-imaging causes of death. This increased level of confidence came at the cost of a higher error rate (16%) [10].

Finally, it is necessary to discuss the impact of organ/organ-system oriented categories of causes of death on the outcome of this study. Earlier work by Roberts et al. has revealed that radiologists struggle with the correct formulation of a cause of death [10]. Working with organ-based categories of causes of death eliminates the usual confusion between errors in *formulating* a cause of death and errors in *diagnosing* a cause of death. However, the pooling of distinct causes of death into broad categories introduces bias for both PMCT (by erasing the diagnostic limitations of PMCT regarding soft tissue details) and macroscopic autopsy (by masking the fact that some pathology can only be diagnosed with a microscope). This effect was certainly noted in the category of HCP which encompasses a wide range of distinct causes of death related to all types of diseases of the heart, the coronary arteries and pulmonary arteries. Some of these are very challenging to distinguish from one another on PMCT but may be recognized at autopsy (e.g. myocardial infarction and pulmonary embolism [8, 10, 24]) whereas others will also be missed if autopsy is not completed histology (e.g. myocarditis or cardiomyopathy). However, causes of death encompassed in the category HPC tend to be natural causes of death and it is worth considering the question if the distinction between different natural cardio-vascular causes of death is relevant to forensic rather than clinical death investigations [10]. Ultimately, forensic death investigations still place a higher emphasis on *manner of death* (i.e. natural death, accident, suicide, homicide) than on *cause of death*.

The combination of positive and negative findings provided by PCMT (presence of findings consistent with sudden cardiac death and absence of conflicting findings) may suffice in some cases to formulate a cause of death based on the balance of probabilities [10, 24]. In other cases, macroscopic autopsy will be necessary to complete an investigation and some will remain uncertain even after histology and toxicology.

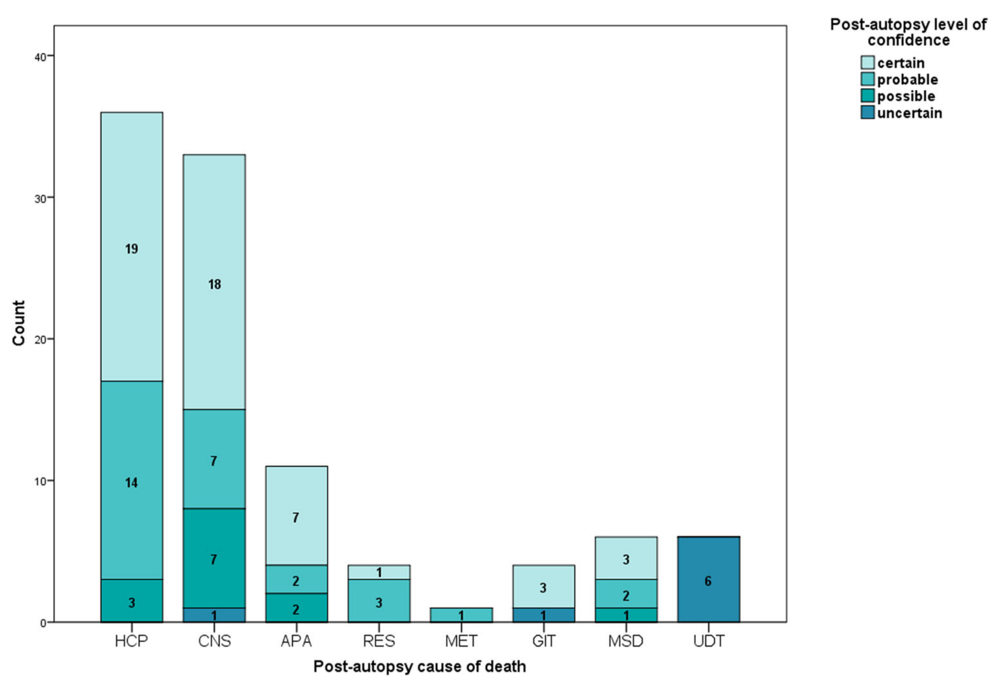
It is beyond the scope of this article to provide guidance regarding the role of PMCT (or autopsy) in forensic death investigations. Answers to the question if or when an imaging may or may not be considered sufficient to conclude a forensic death investigation cannot be provided by science alone, but will strongly vary as a function of political and legal systems, financial resources, availability and training of experts, and local culture and tradition.

Fig. 3 Bar-chart detailing post-imaging levels of confidence in relation to post-imaging categories of causes of death



Several additional limitations of this study deserve discussion. First, forensic pathologists were not blinded to imaging findings when performing their autopsy. This workflow may create bias in favor of the diagnostic accuracy of the post-autopsy cause of death because pathologists were aware of the presence of PMCT findings that

Fig. 4 Bar-chart detailing post-autopsy levels of confidence in relation to post-autopsy categories of causes of death



are hard to detect at autopsy (e.g. pneumothorax or gas embolism or certain fractures such as posterior rib fractures) [6, 10, 11, 40, 41]. However, institutional quality management protocols precluded any changes in the standard stepwise workflow in forensic death investigations. In addition, it is important to emphasize that the aim of the study was not to compare imaging to autopsy, but to compare both post-imaging and post-autopsy cause of death categorization to the final cause of death-categories. Therefore, the bias in favor of autopsy doesn't affect the primary outcome of the study (i.e. the accuracy of categorizing causes of death based on PMCT). Second, the final cause of death was always formulated by the same forensic pathologists who had performed the autopsy. The authors are aware that this may also create bias in favor of the diagnostic accuracy of autopsy. Finally, the study population was relatively small. A larger study population would have provided results with higher power, but the causes of death covered by these 101 cases appears to be representative of our case work.

Conclusions

In this study categorization of causes of death based on non-contrast enhanced PMCT alone, and on PMCT and macroscopic autopsy together, proved to be consistent with the final cause of death-category as determined based on all available information including PMCT, autopsy, and (if available) histology and/or toxicology in more than 82% and 89% of all cases, respectively.

Overall, rater levels of confidence regarding causes of death categorization were lower post-imaging than post-autopsy, but consistency between levels of confidence and accuracy of causes of death categorization was higher post-imaging than post-autopsy. These results underline the fact that the diagnostic potential of PMCT goes beyond the assessment of trauma cases.

Key points

- PMCT is routinely used in forensic death investigations but its role is often limited to the assessment of skeletal injury, gas collections and foreign bodies.
- Non-contrast PMCT has a high accuracy regarding the categorization of organ-based causes of death in comparison to the final forensic report.
- Mean accuracy of PMCT was 82%; only 7% below mean accuracy of autopsy regarding the categorization of organ-based categories of causes of death (89%).
- Post-imaging rater confidence levels are highly consistent with accuracy of post-imaging cause of death categorization: high levels of confidence indicate high accuracy.

Acknowledgements The authors are grateful to Emma Louise Kessler, MD for her generous donation to the Institute of Forensic Medicine, University of Zurich, Switzerland.

Compliance with ethical standards This study received no external funding.

Conflict of interest The authors have no conflict of interest to report.

Ethical approval This study was performed with human cadavers. Ethical approval was waived by the responsible ethics committee (Ethics Committee of the Canton of Zurich) (KEK ZH-Nr. 15-0686). This article does not contain any studies with (living) human participants or animals performed by any of the authors.

References

1. Baglivo M, Winklhofer S, Hatch GM, Ampanozi G, Thali MJ, Ruder TD. The rise of forensic and post-mortem radiology – analysis of the literature between the year 2000 and 2011. J Forensic Radiol Imaging. 2013;1:3–9.
2. Rutty GN, Morgan B, O'Donnell C, Leth PM, Thali M. Forensic institutes across the world place CT or MRI scanners or both into their mortuaries. J Trauma. 2008;65:493–4.
3. Bedford PJ. Routine CT scan combined with preliminary examination as a new method in determining the need for autopsy. Forensic Sci Med Pathol. 2012;8:390–4.
4. Ruder TD. What are the greatest challenges or barriers to applying post-mortem imaging in pediatric radiology? Pediatr Radiol. 2015;45:479.
5. Hatch GM, Dedouit F, Christensen AM, Thali MJ, Ruder TD. RADid: a pictorial review of radiologic identification using post-mortem CT. J Forensic Radiol Imaging. 2014;2(2):52–9.
6. Thali MJ, Yen K, Schweitzer W, Vock P, Boesch C, Ozdoba C, et al. Virtopsy, a new imaging horizon in forensic pathology: virtual autopsy by postmortem multislice computed tomography (MSCT) and magnetic resonance imaging (MRI)–a feasibility study. J Forensic Sci. 2003;48:386–403.
7. Leth PM. Computerized tomography used as a routine procedure at postmortem investigations. Am J Forensic Med Pathol. 2009;30:219–22.
8. Traill Z. The role of computed tomography and magnetic resonance imaging in the investigation of natural death. Diagnostic Histopathol. 2010;16:560–4.
9. Roberts IS, Benamore RE, Peebles C, Roobottom C, Traill ZC. Technical report: diagnosis of coronary artery disease using minimally invasive autopsy: evaluation of a novel method of post-mortem coronary CT angiography. Clin Radiol. 2011;66:645–50.
10. Roberts IS, Benamore RE, Benbow EW, Lee SH, Harris JN, Jackson A, et al. Post-mortem imaging as an alternative to autopsy in the diagnosis of adult deaths: a validation study. Lancet. 2012;379:136–42.
11. Leth PM, Thomsen J. Experience with post-mortem computed tomography in Southern Denmark 2006-11. J Forensic Radiol Imaging. 2013;1:161–6.
12. Leth PM. Virtual autopsy. Forensic Sci Med Pathol. 2013;9:432.

13. Daly B, Abboud S, Ali Z, Sliker C, Fowler D. Comparison of whole-body post mortem 3D CT and autopsy evaluation in accidental blunt force traumatic death using the abbreviated injury scale classification. Forensic Sci Int. 2013;225:20–6.
14. Ampanozi G, Thali MJ. Forensic imaging. In: Madea B, editor. Handbook of forensic medicine. Chichester: Wiley-Blackwell; 2014. p. 153–60.
15. Kasahara S, Makino Y, Hayakawa M, Yajima D, Ito H, Iwase H. Diagnosable and non-diagnosable causes of death by postmortem computed tomography: a review of 339 forensic cases. Leg Med (Tokyo). 2012;14:239–45.
16. Blokker BM, Wagensveld IM, Weustink AC, Oosterhuis JW, Hunink MG. Non-invasive or minimally invasive autopsy compared to conventional autopsy of suspected natural deaths in adults: a systematic review. Eur Radiol. 2016;26:1159–79.
17. Westphal SE, Apitzsch JC, Penzkofer T, Kuhl CK, Mahnken AH, Knüchel R. Contrast-enhanced postmortem computed tomography in clinical pathology: enhanced value of 20 clinical autopsies. Hum Pathol. 2014;45:1813–23.
18. Westphal SE, Apitzsch J, Penzkofer T, Mahnken AH, Knüchel R. Virtual CT autopsy in clinical pathology: feasibility in clinical autopsies. Virchows Arch. 2012;461:211–9.
19. Le Blanc-Louvry I, Thureau S, Duval C, Papin-Lefebvre F, Thiebot J, Dacher JN, et al. Post-mortem computed tomography compared to forensic autopsy findings: a French experience. Eur Radiol. 2013;23:1829–35.
20. Weustink AC, Hunink MG, van Dijke CF, Renken NS, Krestin GP, Oosterhuis JW. Minimally invasive autopsy: an alternative to conventional autopsy? Radiology. 2009;250:897–904.
21. Poulsen K, Simonsen J. Computed tomography as routine in connection with medico-legal autopsies. Forensic Sci Int. 2007;171:190–7.
22. Hatch GM, Ampanozi G, Thali MJ, Ruder TD. Validation of left ventricular circumferential area as a surrogate for heart weight on postmortem computed tomography. J Forensic Radiol Imaging. 2013:198–201.
23. Winklhofer S, Berger N, Ruder T, Elliott M, Stolzmann P, Thali M, et al. Cardiothoracic ratio in postmortem computed tomography: reliability and threshold for the diagnosis of cardiomegaly. Forensic Sci Med Pathol. 2014;10:44–9.
24. Ruder TD, Paula P, Hatch GM, Ampanozi G, Thali MJ, Schweitzer W. Science into practice: post-mortem imaging provides conclusive evidence in a non-suspicious death. J Forensic Radiol Imaging. 2015;2:80–4.
25. Ampanozi G, Flach PM, Fornaro J, Ross SG, Schweitzer W, Thali MJ, et al. Systematic analysis of the radiologic findings of aortic dissections on unenhanced postmortem computed tomography. Forensic Sci Med Pathol. 2015;11:162–7.
26. Ampanozi G, Held U, Ruder TD, Ross SG, Schweitzer W, Fornaro J, et al. Pulmonary thromboembolism on unenhanced postmortem computed tomography: feasibility and findings. Leg Med (Tokyo). 2016;20:68–74.
27. Mueller SL, Thali Y, Ampanozi G, Flach PM, Thali MJ, Hatch GM, et al. Distended diameter of the inferior vena cava is suggestive of pulmonary thromboembolism on unenhanced post-mortem CT. J Forensic Radiol Imaging. 2015;3:38–42.
28. Winklhofer S, Surer E, Ampanozi G, Ruder T, Stolzmann P, Elliott M, et al. Post-mortem whole body computed tomography of opioid (heroin and methadone) fatalities: frequent findings and comparison to autopsy. Eur Radiol. 2014;24:1276–82.
29. Rohner C, Franckenberg S, Schwendener N, Oestreich A, Kraemer T, Thali MJ, et al. New evidence for old lore–urinary bladder distension on post-mortem computed tomography is related to intoxication. Forensic Sci Int. 2013;225:48–52.
30. Schweitzer W, Thali M, Giugni G, Winklhofer S. Postmortem pulmonary CT in hypothermia. Forensic Sci Med Pathol. 2014;10:557–69.
31. Hyodoh H, Watanabe S, Katada R, Hyodoh K, Matsumoto H. Postmortem computed tomography lung findings in fatal of hypothermia. Forensic Sci Int. 2013;231:190–4.
32. Radiological Society of North America. Radiology Reporting Initiative. 2016. http://www.rsna.org/reporting_initiative.aspx. Accessed 28 Dec 2016.
33. Marcovici PA, Taylor GA. Journal Club: structured radiology reports are more complete and more effective than unstructured reports. AJR. 2014;203:1265–71.
34. Schwartz LH, Panicek DM, Berk AR, Li Y, Hricak H. Improving communication of diagnostic radiology findings through structured reporting. Radiology. 2011;260:174–81.
35. Schweitzer W, Bartsch C, Ruder TD, Thali MJ. Virtopsy approach: structured reporting versus free reporting for PMCT findings. J Forensic Radiol Imaging. 2014;2:28–33.
36. Flach PM, Gascho D, Schweitzer W, Ruder TD, Berger N, Ross SG, et al. Imaging in forensic radiology: an illustrated guide for postmortem computed tomography technique and protocols. Forensic Sci Med Pathol. 2014;10:583–606.
37. World Health Organization. Medical certification of cause of death: instructions for physicians on use of international form of medical certificate of cause of death. 1979. http://apps.who.int/iris/handle/10665/40557. Accessed 28 Dec 2016.
38. Hanzlick R. Protocol for writing cause-of-death statements for deaths due to natural causes. Arch Intern Med. 1996;156:25–6.
39. Landis GR, Koch GG. The measurement of observer agreement for categorical data. Biometrics. 1977;33:159–74.
40. Leth PM, Struckmann H, Lauritsen J. Interobserver agreement of the injury diagnoses obtained by postmortem computed tomography of traffic fatality victims and a comparison with autopsy results. Forensic Sci Int. 2013;225:15–9.
41. Schulze C, Hoppe H, Schweitzer W, Schwendener N, Grabherr S, Jackowski C. Rib fractures at postmortem computed tomography (PMCT) validated against the autopsy. Forensic Sci Int. 2013;233:1–3.