Computed Tomography in Forensic Medicine

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This thesis is based on the following publications:

1. Leth PM, Thomsen JL. Experience with post-mortem computed tomography in Southern Denmark 2011-06. Journal of Forensic Radiology and Imaging 2013; 1:161-166. Original research article (1).
2. Precht H, Leth PM, Falk E, Gerke O, Thygesen J, Hardt-Madsen M, Nielsen B, Lambrechtsen J, Egstrup K. Optimization of cardiac computed tomography compared to optical coherence tomography and histopathology: a post-mortem study. Journal of Forensic Radiology and Imaging 2014; 2:85-90. Technical note (2).
3. Leth PM, Struckmann H, Lauritsen J. Interobserver agreement of the injury diagnosis obtained by post-mortem computed tomography of traffic fatality victims and a comparison with autopsy results. Forensic Science International 2012; 225:15-9. Original research article (3).
4. Leth PM, Christensen MR. Computerized tomography used for investigation of homicide victims. Scandinavian Journal of Forensic Science 2011; 17:11-6. Original research article (4).
5. Leth PM, Boldsen JL. Struck by a lance through his side. The homicide of King Canute the Saint. Scandinavian Journal of Forensic Science 2010; 16:24-7. Case story (5).
6. Leth PM, Ibsen M. Abbreviated injury scale scoring in traffic fatalities: Comparison of computerized tomography and autopsy. Journal of Trauma 2010;68:1413-6. Original research article (6).
7. Leth PM. Computerized tomography used as a routine procedure at post-mortem investigations. American Journal of Forensic Medicine and Pathology 2009; 30:219-22. Original research article (7).
8. Leth PM, Worm-Leonhard M. Tablet residues in stomach content found by routine post-mortem CT. Forensic Science International 2008; 179:16-7. Case story (8).
9. Fenger-Grøn J, Kock K, Nielsen RG, Leth PM, Illum N. Spinal cord injury at birth: a hidden causative factor. Acta Paediatrica 2008; 97:824-6. Case story (9).
10. Leth PM. Status of routine post-mortem computerized tomography in Odense, Denmark. Scandinavian Journal of Forensic Science 2008; 14:27-29. Original research article (10).
11. Pøhlsgaard C, Leth PM. Post-mortem CT-coronary angiography. Scandinavian Journal of Forensic Science 2007; 13:8-9. Technical note (11).
12. Leth P. The use of CT scanning in forensic autopsy. Forensic Science, Medicine and Pathology 2007; 3:65-9. Original research article (12).

INTRODUCTION

Computed tomography (CT) and other modern diagnostic imagining techniques, such as magnetic resonance imaging, are now gaining popularity in forensic medicine (7, 14-19). Denmark has been part of this development since the beginning. The Institute of Forensic Medicine at the University of Southern Denmark acquired a helical CT scanner in 2006, and it has since been used in the daily autopsy routine. Forensic imaging is a new method and constitutes a rapidly developing research area (20-23). This thesis presents research on post-mortem CT (PMCT) from the University of Southern Denmark. It is based on the 12 papers listed above (7 original research studies, 2 technical notes, and 3 case studies) and follows the usual thesis structure, with chapters entitled *Materials and methods, Results,* and *Discussion.* The thesis addresses the following research questions:

1. In how many cases can the cause of death be established by PMCT, and what characterises these cases?
2. What is the inter-method variation between autopsy and PMCT with regard to disease and injury diagnoses?
3. Can PMCT be used as a screening tool for selecting cases for autopsy, and can PMCT in some cases substitute for autopsy?
4. What is the inter-observer variation in PMCT? Who should evaluate the images?
5. How much new information is obtained by the histological examination of tissue samples?
6. Can PMCT be used for Abbreviated Injury Scale (AIS) scoring and Injury Severity Scoring (ISS) of traffic fatalities?
7. How can coronary PMCT angiography (PMCTA) be used to optimise clinical CT of the coronary arteries?

8. How can PMCT contribute to forensic autopsies?

MATERIALS AND METHODS

This thesis is based on deceased individuals who were CT-scanned and autopsied at the Institute of Forensic Medicine at the University of Southern Denmark in 2006-2011. The Institute provides forensic service for the 730,000 inhabitants of Southern Denmark. The cases in question were forensic cases selected for autopsy by police authorities at medico-legal inquests. The homicide rate in Denmark is low, and suicide victims are rarely autopsied.

The largest of the investigations (1) included 900 forensic cases from the period 2006-2011 (45% accidents, 40% natural deaths, 7% suicides, 4% homicides, 4% unknown). A total of 172 cases (19%) were drug addicts, 177 (20%) were chronic alcohol abusers, and 105 (12%) were psychiatric patients.
The scanner was a Siemens Somatom Spirit dual-slice CT scanner. The scanning protocols are summarised in **table 1**.

Contrast was not used. The head, neck, thorax, and abdomen, including the proximal femur, were scanned separately. In most cases, the body was scanned naked, without metallic objects, and with the arms fixed above the head when scanning the thorax and abdomen. Suspected homicide cases and severely decomposed bodies were scanned fully clothed in the body bags. The extremities were scanned in trauma cases and if the external examination aroused suspicion of fracture or luxation. A board-specialised forensic pathologist with experience in forensic radiology evaluated the CT images. He had no prior knowledge of the autopsy results but had access to information from the police records, medical records, and external examination of the body. The PMCT diagnoses were thus based on clinical history, an external examination of the body, and the CT images. Imaging was performed immediately before the autopsy, and both PMCT and autopsy were performed on the day of or the day after the medico-legal inquest. The CT images were viewed at a Siemens Syngo Multi-Modality workstation (software syngoMMWP version VE31A). Axial cross-sections, multiplanar reconstructions (MPR), maximal intensity projections (MIP), and volume-rendered images were used.

	Head	Neck	Thorax	Abdomen	Extremities
mA	110	110	60	80	30
kV	130	130	130	130	130
Slice	1 mm	3 mm	5 mm	5 mm	3 mm
Collimation	1 mm	1.5 mm	2.5 mm	2.5 mm	1.5 mm
Pitch	0.95	0.95	1.8	1.8	1.0
Rotation time	1.5 s	1.5 s	1.0 s	1.0 s	1.0 s
Kernel	Median smooth H31 Sharp H60	Median sharp B50	Median smooth B31 High-res B70	Median B41	Ultra-high-res U90

Table 1: Scan protocols used for PMCT at the Institute of Forensic Medicine, University of Southern Denmark, since 2006.

The autopsy was undertaken by a board-specialised forensic pathologist according to the Danish government's official guidelines. The Institute is accredited according to ISO 17026. The examiner was blinded to the PMCT findings. All body cavities, including the neurocranium, were opened. The pleural cavities were opened under water. The diagnoses based on CT and autopsy were obtained prospectively and registered independently of each other. All diagnoses were coded, and we registered how each diagnosis was obtained (autopsy, PMCT, or both). Injury diagnoses were coded according to the abbreviated injury scale (AIS), a coding system widely used by trauma centres. All non-traumatic diagnoses were coded according to the World Health Organization's (WHO's) International Classification of Diseases (ICD-10). Each diagnosis was also given a code associated with anatomical location and type of pathology (e.g., liver/fatty degeneration or cerebrum/ contusion) following a coding system used at our institute. The cause of death based on PMCT and autopsy and the mode of death were registered. The cause of death diagnosis was registered according to ICD-10 and a coding system used by departments of forensic medicine in Denmark. We also registered by which methods the cause of death was established (PMCT, autopsy, toxicology, histology, or medical history).
The forensic pathologist who evaluated the CT images decided whether an autopsy could be omitted according to a set of predetermined criteria (**table 2**).

The decision was based on information from the police record, the external examination of the body, and the scan results and was a purely theoretical exercise performed to answer research question 3. The decision could then be re-evaluated when the autopsy results became known.

Information gained by the histological examination was registered. Samples for microscopy were taken from all internal

Autopsy not needed
Not suspicious according to the police record
No suspicious findings at the scene
Nothing suspicious upon external examination of the body
PMCT or toxicology provides a likely cause of death, and PMCT answers relevant questions
Autopsy needed
Homicides
Suspicious case according to police record
Suspicious findings at the scene
Suspicious findings upon external examination of the body
No cause of death provided by PMCT
Relevant questions not answered by PMCT
PMCT findings that need clarification

Table 2: Criteria for deciding whether an autopsy is needed or if the history, external examination of the body, and PMCT images provide sufficient information.

organs, bone marrow, skin, and skeletal muscle, except from severely decomposed bodies. We also recorded whether the deceased individuals had been diagnosed with a major psychiatric disease or had been abusing drugs and/or alcohol, whether the body was decomposed, and whether the case belonged to any of the following categories: sudden unexpected death in adults; sudden infant death syndrome (SIDS); road traffic accident; exposure to a cold environment; drowning; diving death; death in custody; work-related disease or accident; sports-related death; perinatal death; death related to medical treatment; and identification cases.

Data were entered into a computer database (SPSS Statistics 18.0) with the diagnosis code as the unit of analysis. In the studies included in this thesis, the following statistical methods were employed: chi-square test for evaluating heterogeneity in contingency tables; t-test for comparisons of means; κ-values for assessing reproducibility of diagnoses; and sensitivity, specificity, and prognostic values for the PMCT diagnoses. Autopsy was the gold standard for findings visualised by autopsy (inner organs, ribcage, cranial base, and cranial vault).

RESULTS

1. Cause of death

In an investigation of 900 autopsies (1), we found agreement regarding the cause of death in 66% (N=425) of cases, including 14% (N=91) of cases in which the cause of death was unknown based on both PMCT and autopsy. **Table 3** is a cross-table of cause-of-death diagnoses obtained by autopsy and PMCT. When a cause of death was given, the agreement between autopsy and PMCT was high (94%, N=334/355); however, in 45% (N=287) of cases, no cause of death could be found by PMCT. This percentage is much higher than the proportion of unknown causes of death based on autopsy, which was 15% (N=98). These statistics do not include the 258 cases in which the cause of death was established by toxicology.

A high proportion (44%, N=127) of the individuals whose cause of death could not be established by PMCT were shown by autopsy to have died from a cardiovascular disease. The agreement between PMCT and autopsy was highest when the mode of death was an accident (85%, N=181/213) and much lower (48%, N=159/337) when the mode of death was natural. The agreement was high for homicides and suicides (>90%).

2. Inter-method agreement

In an investigation of 900 forensic cases (1), we found that 70% of non-injury diagnoses and 65% of injury diagnoses were obtained by both autopsy and PMCT (**tables 4-6**). PMCT was unable to detect some important non-injury diagnoses, including cardiovascular diagnoses (coronary thrombosis, acute myocardial infarction, fibrotic myocardial scar, pulmonary embolism), oesophageal varices, and non-perforated gastrointestinal ulcerations. Coronary atherosclerosis could easily be detected if the lesions were calcified, but it was not possible to evaluate the degree of stenosis. PMCT was good at detecting major haemorrhages, air and fluid collections, fatty liver, hyper- and hypotrophy, neoplasms, cysts, gallstones and kidney stones, aneurysms, and cerebral haemorrhages.

PMCT was superior to autopsy in detecting fractures in the facial skeleton, spine, and extremities, but it was less reliable in detecting injuries in the inner organs, small haematomas, and aortic transections. Non-displaced cranial and rib fractures and intervertebral disc lacerations were not always visualised by PMCT. Three epidural haematomas were all detected by both PMCT and autopsy. Subdural haematomas were detected by both PMCT and autopsy in 73% (N=17/23) of cases and by PMCT or autopsy alone in 13% (N=3/23) of cases each. The subdural haematomas over

Cause of death	**PMCT**	Disease						Injury									
Autopsy		Cadiovascular	Lung	CNS	GI/ liver	Cancer	Sepsis	CNS	Thorax	Multiple	Other injury	Burns	Suffocation	Exposure	Unknown	Toxicology	Total
Disease	Cardiovascular	***55***	*5*	*0*	*1*	*1*	0	0	0	0	0	0	0	0	127		189
	Lung	*0*	***21***	*0*	*0*	*0*	0	0	0	0	0	0	0	0	7		28
	CNS	0	0	**14**	0	0	0	0	0	0	0	0	0	0	3		17
	GI/liver	2	0	0	**10**	0	0	0	0	0	1	0	0	0	24		37
	Cancer	0	0	0	0	**12**	0	0	0	0	0	0	0	0	2		14
	Sepsis	0	0	0	0	0	**0**	0	0	0	0	0	0	0	7		7
Injury	CNS	1	0	0	0	0	0	**44**	0	0	0	0	0	0	1		46
	Thorax	0	0	0	0	0	0	1	**23**	0	1	0	0	0	2		27
	Multiple	0	0	0	0	0	0	0	0	**93**	0	0	0	0			93
	Other injury	1	0	0	0	0	0	0	0	0	**6**	0	0	0	7		14
	Burns	0	0	0	0	0	0	0	0	0	0	**7**	0	0	1		8
	Suffocation	0	0	0	0	0	0	0	0	0	0	0	**44**	0	14		58
	Exposure	0	0	0	0	0	0	0	0	0	0	0	0	**5**	1		6
	Unknown	4	3	0	0	0	0	0	0	0	0	0	0	0	**91**		98
Toxicology																	258
	Total	63	29	14	11	13	0	45	23	93	8	7	44	5	287	258	900

Table 3: Cross-table displaying the numbers of cause-of-death diagnoses (grouped by organ system) obtained by autopsy, PMCT, and toxicology in 900 deceased individuals who were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, between 2006 and 2011.

Diagnosis	N	CT+ AU	Only AU	Only CT
Atherosclerosis	666	606	53	7
Hyperplasia/ hypertrophy	269	219	45	5
Fluid in body cavity	263	211	9	43
Steatosis	213	186	10	17
Implant	109	91	7	11
Surgically removed organ	108	68	37	3
Foreign substance	95	28	53	14
Hypoplasia/ hypotrophy	88	54	6	28
Oedema	88	65	23	0
Malignant neoplasm	88	60	15	13
Diffuse inflammatory condition	81	31	33	17
Lithiasis	71	49	13	9
Nephrosclerosis	63	8	52	3
Scar tissue in organ	59	7	47	5
Benign neoplasm	53	30	22	1
Blood in body cavity	47	40	5	2
Emphysema	46	31	4	11
Cyst	44	38	3	3
Thrombosis	41	1	40	0
Cirrhosis	40	4	35	1
Healed infarction	34	19	8	7
Acute infarction	31	6	24	1
Calcification	30	24	1	5
Chronic gastrointes-tinal ulceration	27	27	0	0
Struma	25	24	1	0
Distension**	24	16	7	1
Aneurysm	23	18	4	1
Acute gastrointesti-nal ulceration	22	0	22	0
Thromboembolism	21	0	21	0
Pleura plaques	19	13	5	1
Chronic inflammatory condition	16	11	3	2
Air (pneumothorax, -encephalon)	15	10	0	5
Abscess	10	6	3	1
Hernia	7	4	1	2
Dissecting aneurysm	7	4	3	0
Oesophageal varices	6	0	6	0
Pus in body cavity	2	2	0	0
Other	162	103	50	9
Total	3013	2114	671	228

*E.g. soot/duckweed in airways (fire, drowning), **E.g., hydronephrosis, bronchiectasia

Table 4: Deceased individuals who were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, between 2006 and 2011. Non-injury pathology diagnoses distributed by diagnostic method (autopsy (AU), PMCT (CT), or both).

looked by PMCT were all small. The subdural haematomas diagnosed by PMCT but not found by autopsy were most likely artefacts caused by post-mortem blood sedimentation in the transverse sinus (24). Traumatic subarachnoid haemorrhages were found by both PMCT and autopsy in 67% (N=34/51) of the cases and by autopsy alone in 27% (N=14/51) of the cases, while the diagnosis of subarachnoid haematoma by PMCT could not be confirmed by autopsy in 3 cases.

3. PMCT as a screening tool

Whether PMCT can be used as a screening tool for selecting cases to autopsy was investigated in three of the studies included in the thesis (1, 7, 12). In the largest of these studies (1), it was estimated that autopsy could be substituted by PMCT in 21% (N=136) of the 642 non-toxicology cases (15% of all 900 cases). Important autopsy findings were missed by PMCT in only 6% (N=8) of these cases. The rates of agreement with autopsy regarding the cause of death in the groups where it was estimated that PMCT could and could not substitute for autopsy were 98% and 57%, respectively. The former group contained a significantly higher proportion of accident victims (77%, N=105) and a lower proportion of natural deaths (15%, N=20). It was estimated that PMCT could have substituted for autopsy in 50% (N=129) of the 259 individuals who died from poisoning if the toxicology results had been available before the body was released, resulting in a total of 29% (N=265) of cases where PMCT could have substituted for autopsy if a day-to-day toxicology service had been available.

4. Inter-observer variation

The inter-observer variation of PMCT injury diagnoses between a forensic pathologist and a radiologist was evaluated in a study of 67 traffic fatality victims (3) with 994 AIS injury diagnoses. The purpose of the study was to estimate the validity of PMCT injury diagnoses by studying the differences in the diagnostic pattern between two observers with different educational backgrounds, as well as to compare the validated PMCT diagnoses with autopsy diagnoses. The PMCT and autopsy diagnoses were obtained and registered independent of each other by two different pathologists, and a board-certified radiologist later re-evaluated the PMCT images without prior knowledge of the primary PMCT or autopsy diagnoses. The radiologist was trained in clinical CT but had no previous experience with PMCT. The pathologist had five years of experience in PMCT but was not a board-certified specialist in radiology.

The study showed a substantial inter-observer agreement (κ=0.65), although there were some important differences. The radiologist diagnosed more injuries than the pathologist, especially in the spine and face. In addition, the radiologist diagnosed more lesions in the skeletal system, whereas the pathologist diagnosed more injuries in the organs and soft tissues. The difference between the two observers was greatest when the diagnoses had a low AIS severity score. The κ-values were 0.51 for the injuries with the lowest AIS severity score and 0.87 for the injuries with the highest score. **Figure 1** shows how the PMCT diagnoses were distributed between the two observers. **Tables 7**, **8** and **9** show the distribution of the injuries according to the observer and the type of tissue that was injured (skeletal/organ/blood or air accumulation), as well as the AIS region and the AIS severity score.

Diagnosis	N	CT+AU	Only AU	Only CT	Sensitivity	Specificity	Predictive value
Head							
Cerebral atrophy	70	37	5	28	0.88	0.97	0.56
Healed cerebral infarction	31	18	6	7	0.75	0.99	0.72
Cerebral atherosclerosis	13	3	10	0	0.23	1.00	1.00
Cerebral haemorrhage	9	7	1	1	0.88	1.00	0.88
Basal subarachnoid haemorrhage	7	7	0	0	1.00	1.00	1.00
Fresh cerebral infarction	6	5	0	1	1.00	1.00	0.83
Neck							
Struma	26	25	1	0	0.96	1.00	0.96
Thyroid adenoma	6	4	1	1	0.80	1.00	0.80
Oesophageal varices with bleeding	4	0	4	0	UD	1.00	UD
Thorax							
Coronary atherosclerosis	319	278	38	3	0.88	1.00	0.99
Cardiac hypertrophy	138	130	6	2	0.96	1.00	0.98
Hydrothorax	104	95	0	8	1.00	0.99	0.92
Pulmonary oedema	82	64	18	3	0.78	1.00	0.96
Pulmonary emphysema	42	27	4	11	0.87	0.99	0.71
Pneumonia	40	20	3	17	0.87	0.98	0.54
Myocardial fibrotic scar	39	1	36	2	0.03	1.00	0.33
Coronary thrombosis	33	1	32	0	0.03	1.00	1.00
Pulmonary embolism	21	0	21	0	UD	1.00	UD
Acute myocardial infarction	17	1	16	0	0.06	1.00	1.00
Pleura plaques	19	13	5	1	0.72	1.00	0.93
Calcification of aortic valve	13	11	0	2	1.00	1.00	0.85
Hydropericardium	12	11	0	1	1.00	1.00	0.92
Cardiac tamponade	11	11	0	0	1.00	1.00	1.00
Bronchiectasis	11	5	5	1	0.50	1.00	0.83
Right ventricular hypertrophy	10	1	9	0	0.10	1.00	1.00
Pulmonary fibrosis	8	6	0	2	1.00	1.00	0.75
Lung cancer	7	6	1	0	0.86	1.00	1.00
Dissecting aortic aneurysm	7	4	3	0	0.57	1.00	1.00
Mitral valve pathology	6	4	2	0	0.66	1.00	1.00
Non-traumatic haemothorax	4	4	0	0	1.00	1.00	1.00
Abdomen							
Aorta atherosclerosis	329	319	4	4	0.99	0.99	0.99
Hepatic steatosis	214	187	10	17	0.95	0.98	0.92
Splenomegaly	68	67	0	1	1.00	1.00	0.99
Gallbladder stones	55	39	13	3	0.75	1.00	0.93
Benign nephrosclerosis	55	8	44	3	0.15	1.00	0.73
Hepatic cirrhosis	40	4	35	1	0.10	1.00	0.80
Cystis renis	35	33	0	2	1.00	1.00	0.94
Ascites	32	25	1	6	0.96	0.99	0.81
Portal lymph node hyperplasia	32	4	27	1	0.13	1.00	0.80
Chronic peptic ulcer	27	0	27	0	UD	1.00	UD
Acute ventricular stress ulcer	22	0	22	0	UD	1.00	UD
Hypertrophied prostate	17	15	1	1	0.94	1.00	0.94
Acute peritonitis	16	1	15	0	0.06	1.00	1.00
Nephrolithiasis	16	9	1	6	0.90	0.99	0.60
Hydronephrosis	15	9	0	6	1.00	0.99	0.60
Chronic pancreatitis	13	10	2	1	0.83	1.00	0.91
Aortic aneurysm without rupture	10	9	0	1	1.00	1.00	0.90
Ruptured aortic aneurysm	9	9	0	0	1.00	1.00	1.00
Haemoperitoneum, not traumatic	8	8	0	0	1.00	1.00	1.00
Severe renal atrophy	6	5	1	0	0.83	1.00	1.00
Benign ovarian cyst	6	3	3	0	0.50	1.00	1.00
Kidney cancer	4	3	1	0	0.75	1.00	1.00
Intestinal infarction	4	0	4	0	UD	1.00	UD
Total	2186	1587	455	144	0.78	0.76	0.92

Table 5: Deceased individuals who were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, between 2006 and 2011. The most common non-injury diagnoses (count > 3) are distributed by diagnostic method (autopsy (AU), PMCT (CT), or both). Sensitivity, specificity, and positive predictive values were calculated with autopsy findings as the gold standard. UD = undefined.

Diagnosis	Total	CT+AU	Only AU	Only CT	Sensitivity	Specificity	Predictive value
Fracture	**820**	**620**	**44**	**156**			
Cranial vault	45	40	4	1	0.90	1.00	0.97
Cranial base	51	43	7	1	0.86	1.00	0.98
Cranium crush injury	11	11	0	0			
Facial skeleton	94	52	3	39			
Spine	138	57	9	71			
Ribs and sternum	137	117	20	0	0.85	1.00	1.00
Pelvis	55	50	1	4			
Extremities	274	238	0	36			
Other fractures	15	12	0	3			
Contusion/laceration	**499**	**238**	**244**	**17**			
Cerebrum	52	32	19	1	0.63	1.00	0.97
Spinal cord	23	21	1	1			
Lungs	67	46	18	3	0.72	1.00	0.94
Aorta	32	5	27	0	0.16	1.00	1.00
Heart	25	7	18	0	0.28	1.00	1.00
Liver	57	37	20	0	0.65	1.00	1.00
Spleen	32	11	20	1	0.35	1.00	0.92
Kidney	11	4	7	0	0.57	1.00	1.00
Other injuries *	200	75	114	11			
Gunshot wound	**16**	**12**	**4**	**0**	0.75	1.00	1.00
Sharp injurie	**199**	**142**	**57**	**0**	0.71	1.00	1.00
Total	**1534**	**1012**	**349**	**173**			

* other injuries includes extra-axial haemorrhages

Table 6: Deceased individuals who were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, between 2006 and 2011. Injury diagnoses were obtained by grouping AIS diagnoses into broader categories according to diagnostic method (CT=PMCT, AU=autopsy). Sensitivity, specificity, and positive predictive values for PMCT are calculated with autopsy findings as the gold standard. No gold standard was available for the facial skeleton, extremities, spine, or pelvis.

	Diagnosis obtained by both radiologist and patholo-gist	Diagnosis obtained only by radiologist	Diagnosis obtained only by pathologist	Total	κ
Injuries in the skeletal system	491 84 %	82 14 %	9 2 %	582 100 %	0.33
Injuries in organs and soft tissues	70 62 %	13 12 %	29 26 %	112 100 %	0.66
Abnormal air accumu-lations*	61 97 %	2 3 %	0 0 %	63 100 %	-
Haemato-mas in body cavities	67 88 %	5 7 %	4 5 %	76 100 %	0.74
All lesions diagnosed by CT	689 83 %	102 12 %	36 5 %	833 100 %	0.65

*Pneumothorax, pneumoperitoneum, and pneumoencephalon

Table 7. Distribution of AIS injury diagnoses from 67 traffic fatalities in Southern Denmark, 2006-2009, obtained by PMCT, distributed by tissue type and observer, with the κ measure of agreement between observers.

	Diagnosis by radiologist and patholo-gist	Diagno-sis only by radiolo-gist	Diagnosis only by pathologist	Total	κ
Head	110 84 %	18 14 %	3 2 %	131 100 %	0.74
Face	53 70 %	21 28 %	2 3 %	76 101 %	0.02
Neck	2 50 %	0 0 %	2 50 %	4 100 %	0.53
Thorax	177 88 %	14 7 %)	10 5 %	201 100 %	0.81
Abdo-men	19 43 %	5 11 %	20 45 %	44 99 %	0.47
Spine	120 75 %	37 23 %	3 2 %	160 100 %	0.19
Upper extremity	74 97 %)	2 3 %)	0 0 %	76 100 %	0.49
Lower extremity	134 95 %	5 4 %	2 1 %	141 100 %	0.43
All le-sions	689 83 %	102 12 %	42 5 %	833 100 %	0.65

Table 8. Distributions of AIS injury diagnoses from 67 traffic fatalities in Southern Denmark, 2006-2009, obtained from PMCT, distributed by AIS region and observer (radiologist, pathologist, or both).

	Diagnosis by both radiologist and pathologist	Diagnosis only by radiologist	Diagnosis only by pathologist	Total
AIS severity score 1-2	360 78 %	82 18 %	21 5 %	463 101 %
AIS severity score 3-4	276 89 %	20 6 %	15 5 %	311 100 %
AIS severity score 5-6	53 90 %	0 0 %	6 10 %	59 100 %
All lesions diagnosed by CT	689 83 %	102 12 %	42 5 %	833 100 %

Table 9. Distribution of AIS injury diagnoses from 67 traffic fatalities in Southern Denmark, 2006-2009, obtained from PMCT, distributed by AIS severity score and observer (radiologist, pathologist, or both).

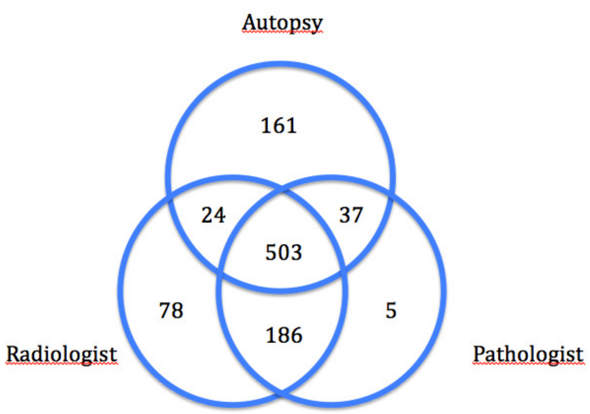

Figure 1: A total of 994 injury diagnoses from traffic fatalities in Southern Denmark distributed by how the diagnosis was obtained. The numbers in the circles indicate the number of diagnoses obtained by autopsy, by CT reviewed by a radiologist, by CT reviewed by a pathologist, and by all possible combinations thereof.

5. Importance of histology

The importance of a histological examination was investigated in three of the studies included in this thesis (1, 7, 12). The largest of these studies (1) showed that the histological examination confirmed the autopsy findings in 59% (N=527) of all cases. Important new information (defined as findings not expected and relevant to the cause of death or other important issues) was obtained in 23% (N=206) of these cases, and some, although less important, new information was obtained in 15% (N=135) of the cases. There were significantly fewer important microscopic findings (7%, N=20) in cases where it had been estimated that an autopsy could be substituted by PMCT.

6. PMCT used to determine the Abbreviated Injury Scale (AIS) score and Injury Severity Score (ISS)

In one of the studies included in this thesis (6), we used the AIS in traffic fatalities based on data from post-mortem computerised tomography (CT) and autopsy for the purpose of evaluating the value of PMCT for AIS-scoring of traffic fatalities. AIS-scoring of trauma patients who are dead on arrival to the hospital is important to eliminate the selection bias that may occur in comparisons of treatment efficiency of different trauma centres due to differences in the fraction of patients who die before reaching the hospital. Centres with a large uptake area and longer ambulance transport times receive more patients who are dead on arrival, and such patients must also be AIS-scored. This scoring may be conducted based on autopsy; however, for practical and legal reasons, it may be preferable to use PMCT.
The AIS-scoring was performed according to the guidelines in the Abbreviated Injury Scale 2005 edition (25). The injuries with the highest AIS scores found by PMCT and autopsy were registered for each of the anatomical regions included in the AIS. Injury severity scores (ISS) based on PMCT and autopsy were also calculated. The investigation included 52 individuals (39 men, 13 women) who were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, from February 2006-May 2007. The causes of death were multiple traumas (56%), chest trauma (21%), head trauma (19%), and abdominal trauma (4%). In total, 87% were dead on arrival, 4% died within the first 12 hours, and 6% died in the following 2-6 days. On average, there was 94% agreement between autopsy and PMCT in detecting the presence or absence of lesions in the various anatomical regions, although there was some variation. **Table 10** shows the frequencies of injuries in the body regions detected by PMCT and autopsy; the relative and absolute numbers of cases where PMCT gave the same, a greater, or a smaller severity score than autopsy in these regions; and the κ-values for the reproducibility of severity scores. The severity scores range from 1-6 (1=minor, 2=moderate, 3=serious, 4=severe, 5=critical, 6=maximal), with 0 for cases with no lesions. On average, the severity scores in the various regions were the same in 90% of all cases (range 75-100%). When different severity scores were obtained, PMCT detected more lesions with a high severity score in the facial skeleton, pelvis, and extremities, whereas autopsy detected more lesions with high scores in soft tissues (especially in the aorta), the cranium, and ribs. PMCT was also slightly better than autopsy in scoring haemorrhages in meninges and pleural cavities and in detecting pneumothorax.

The ISS is based on the AIS score and assesses the combined effects of multiple injuries (25). The ISSs obtained by PMCT and autopsy were calculated and found to be identical in 66% of all cases, with a variation of less than 10 points in 19% of cases, resulting in a total of 85% of cases with no or moderate variation in ISS. The 15% of cases with greater variation in ISS are listed in **table 11**, which also contains an explanation for the variations. The κ-value associated with ISS reproducibility was 0.53.

7. PMCT coronary angiography

We described a method for PMCT coronary angiography on isolated autopsy hearts that was published as a technical note in 2007 (11), and an improved version was published in 2013 (2) in which the method was combined with dual-energy CT and optical coherence tomography (OCT). The latest version was tested on 20 autopsy hearts. With this method, a contrast agent that solidifies after cooling was injected into the coronary arteries. CT scanning

	Body region	Injury present		Severity scores				κ-values for reproducibility of severity scores
		CT	AU	CT = AU	CT > AU	CT < AU	TOTAL	
Head and Neck	Facial skeleton	37 %	25 %	83 % (43)	17 % (9)	0 % (0)	100 % (52)	0.65
	Cranium	52 %	56 %	88 % (46)	2 % (1)	10 % (5)	100 % (52)	0.84
	Cerebrum	54 %	54 %	81 % (42)	12 % (6)	8 % (4)	100 % (52)	0.73
	Cerebellum	14 %	21 %	85 % (44)	2 % (1)	13 % (7)	100 % (52)	0.56
	Brain stem	4 %	8 %	96 % (50)	0 % (0)	4 % (2)	100 % (52)	0.65
	Meninges	52 %	50 %	96 % (50)	4 % (2)	0 % (0)	100 % (52)	0.97
	Neck organs	12 %	33 %	79 % (41)	0 % (0)	21 % (11)	100 % (52)	0.45
	Cervical column	21 %	25 %	96 % (50)	0 % (0)	4 % (2)	100 % (52)	0.81
Thorax	Ribs	79 %	81 %	90 % (47)	2 % (1)	8 % (4)	100 % (52)	0.88
	Lungs	59 %	73 %	65 % (34)	17 % (9)	17 % (9)	99 % (52)	0.54
	Heart	21 %	27 %	90 % (47)	0 % (0)	10 % (5)	100 % (52)	0.81
	Aorta	8 %	33 %	75 % (39)	0 % (0)	25 % (13)	100 % (52)	0.40
	Pleural cavities	60 %	54 %	81 % (42)	19 % (10)	0 % (0)	100 % (52)	0.72
	Pericardial sac	21 %	23 %	96 % (50)	0 % (0)	4 % (2)	100 % (52)	0.90
	Thoracic column	31 %	31 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.0
Abdomen	Liver	39 %	48 %	87 % (45)	2 % (1)	12 % (6)	101 % (52)	0.77
	Spleen	25 %	37 %	85 % (44)	2 % (1)	13 % (7)	100 % (52)	0.68
	Kidneys	8 %	23 %	81 % (42)	0 % (0)	19 % (10)	100 % (52)	0.39
	Gastro Intestinal	0 %	6 %	94 % (49)	0 % (0)	6 % (3)	100 % (52)	0.39
	Peritoneal cavity	11 %	11 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.0
	Lumbar column	6 %	4 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.0
Extremities	Humerus	10 %	10 %	98 % (51)	2 % (1)	0 % (0)	100 % (52)	0.89
	Radius and ulna	11 %	11 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.00
	Hand bones	4 %	4 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.00
	Pelvis	39 %	40 %	88 % (40)	19 % (10)	4 % (2)	100 % (52)	0.66
	Femur	25 %	23 %	98 % (51)	2 % (1)	0 % (0)	100 % (52)	0.95
	Tibia and fibula	29 %	31 %	91 % (47)	8 % (4)	2 % (1)	100 % (52)	0.79
	Foot bones	4 %	4 %	100 % (52)	0 % (0)	0 % (0)	100 % (52)	1.00

Table 10: Frequency of injuries in body regions and severity scores distributed by the correlation between CT and autopsy (AU): relative and absolute numbers of individuals where CT gave the same, a greater, or a smaller severity score than autopsy and the κ-values for the reproducibility of severity scores in traffic fatalities investigated at the Institute of Forensic Medicine, University of Southern Denmark, from February 2006-May 2007.

Case No.	CT	Autopsy	Difference	Explanation for difference
12	27	43	16	Cerebellar lesion scored as 3 on CT and 5 on autopsy
16	33	75	42	Aorta rupture with score 6 not detected by CT
17	50	75	25	Aorta rupture with score 6 not detected by CT
20	43	75	32	Aorta rupture with score 6 not detected by CT
21	50	75	25	Aorta rupture with score 6 not detected by CT
26	34	75	41	Cerebral lesion scored as 4 on CT and 6 on autopsy
28	45	75	30	Aorta rupture with score 6 not detected by CT
45	45	29	16	Tension pneumothorax score 5 detected by CT but not by autopsy
48	29	75	46	Aorta rupture with score 6 not detected by CT

Table 11: Cases of traffic fatalities investigated at the Institute of Forensic Medicine, University of Southern Denmark, from February 2006-May 2007 in which the ISSs obtained by CT and autopsy varied by more than 10, along with an explanation of the variance.

was performed on the heart alone, as well as with the heart in a chest phantom to simulate clinical CT. We used eight different CT protocols and the newest CT technique to image every heart. The OCT and CT images were compared with their corresponding histological sections. A procedure for ensuring the correct alignment of the images was also developed.

8. Contribution of PMCT to forensic autopsy

The general contribution of PMCT to forensic autopsy will be addressed in the *Discussion*. Some results regarding specific case types will be presented here:

Fire fatalities: Thirty (3%) of the deceased individuals in our investigation of 900 forensic cases (1) died in a fire. Twenty-five of these individuals had soot in their airways at autopsy. The soot was not found by PMCT in any case. Four individuals had a pseudo-haematoma in the cranial cavity; three of these pseudo-haematomas were found by PMCT, and the one not found was small.

Identifications: Twenty-six (3%) of the deceased in our investigation of 900 forensic cases (1) were unidentified. Fifteen were identified by odontology, 6 by DNA, and 5 by other findings. In all of the latter cases, PMCT provided some information, and in one case, a comparison with ante-mortem CT was conclusive. A total of 9 implants and 3 healed fractures were found among these 30 cases.

Traffic fatalities: We found that PMCT provided a good overview of fracture systems in traffic fatalities (and in other victims of severe trauma). Fractures were seen in situ, which facilitated the evaluation of severe cranial fractures or fractures of the lower extremities, where the presence of an intermediary fragment indicated the direction of the trauma.

Drowning: Our investigation of 900 forensic cases (1) included 24 drowning cases. PMCT showed a patchy mosaic pattern of hyperdense areas, most likely caused by aspiration of water into the lungs in 58% of cases (N=14), pleural effusions in 33% (N=8), fluid in the paranasal sinuses in 67% (N=16), and fluid in the ventricle in 42% (N=10) of cases. It is our experience that more fluid, sometimes visibly foamy fluid, is found by PMCT in the main bronchi and trachea in drowning cases than is otherwise seen post-mortem, but this observation was not registered. A more detailed study that separates cases of salt- and freshwater drowning will be performed in the near future.

Bolus death: We had 7 cases of bolus death (5 men, 1 woman, 1 child) among the 900 forensic cases that were included in paper 1. Four of the individuals were alcoholics, 1 suffered from oligophrenia, 1 suffered from muscle dystrophy, and 1 was a child. The acute care physicians had removed two of the boli (one from the child and one from an adult). The rest of the boli were all visible on PMCT (4 in the pharynx and 1 in the trachea/ 3 meat lumps, 1 piece of broccoli and 1 raisin cake). All boli in the pharynx were located in both the oropharynx and the hypopharynx. The meat lumps were relatively homogeneous, with HU values of approximately 35, whereas the broccoli and the cake were heterogeneous, with average HU values of 20 (-435 to 70) and 20 (-250 to 125), respectively.

Homicides: In an examination of 26 homicide victims (4), we found a total of 228 injuries. Injuries were divided into contusions (blunt-force tissue injury without a macroscopic breach of tissue continuity), lacerations (blunt-force tissue injury with a macroscopic breach of tissue continuity), fractures, sharp-force injuries, internal injuries caused by a bullet, foreign bodies, haematomas, and oedema. There were four cases of death due to monoxide poisoning caused by arson in which no injuries were found. The proportion of injuries found by autopsy and PMCT, distributed by injury type, is shown in **table 12**. Sharp-force injuries divided by anatomic location and detection method are shown in **table 13**. PMCT did not detect 2 of 4 contusions (1 lung and 1 brain contusion), 26 of 109 sharp-force injuries, 10 of 27 haematomas, and 1 of 1 case of diffuse subarachnoid bleeding. PMCT did, however, detect 2 cases of pneumothorax, 2 fractures, 1 haematoma, 1 projectile, and 4 pieces of shrapnel not found by autopsy. A load of shotgun pellets in the thorax found in one case was not included in these statistics. Six of the ten haematomas not found by CT were small but important haematomas in the soft tissue of the neck in cases of strangulation. In these cases, both autopsy and PMCT detected 2 hyoid fractures, 1 thyroid fracture, and 1 cricoid fracture. One small haematoma in the extra cranial soft tissue was not identified by PMCT. Four extremity fractures were only detected by PMCT. PMCT did not detect two fractures of the cranial base found at autopsy. One 9-mm bullet and 4 pieces of shrapnel were primarily found by PMCT. PMCT detected two cases of pneumothorax that were not found by autopsy, one of which was a case of pressure pneumothorax.

Tablet residues in the stomach: We previously published a case report (8) detailing the PMCT findings of the medico-legal investigation into the death of an adult male where the circumstances of death raised the possibility of intentional overdose. PMCT showed radio-opaque material in the stomach with a HU value of 290 (**figure 15**), and the toxicological analysis revealed a lethal concentration of codeine and salicylic acid in the blood. The radio-opacity in this case was due to magnesium hydroxide, which is a component of non-prescription medications containing codeine and acetylsalicylic, which were found at the scene of death.

	Detected by autopsy only	Detected by CT only	Detected by autopsy and CT	Total
Contusion	2	0	2	4
Laceration	0	0	5	5
Sharp injuries	26	0	83	109
Gunshot injuries	0	0	11	11
Fracture	2	4	27	33
Haematoma	10	1	16	27
Oedema	0	0	2	2
Haemothorax	0	0	13	13
Haemoperitoneum	0	0	1	1
Basal subarachnoid bleeding	0	0	1	1
Diffuse subarachnoid bleeding	1	0	2	3
Subdural haematoma	0	0	1	1
Pneumothorax	0	2	4	6
Projectiles	0	1	2	3
Shrapnel	0	4	5	9
Total	41	12	175	228

Table 12: Internal injuries and foreign bodies found in homicide victims from Southern Denmark, 2006-2009, divided by injury type and detection method (autopsy or CT).

Structure	Detected by autopsy only	Detected by CT only	Detected by CT and autopsy	Total
Lungs	11	0	32	43
Bones	0	0	27	27
Soft tissue	4	0	9	13
Heart	3	0	4	7
Liver	0	0	6	6
GI tract	5	0	1	6
Artery	3	0	1	4
Kidney	0	0	1	1
Eye	0	0	1	1

Table 13: Sharp injuries found in homicide victims from Southern Denmark, 2006-2009, divided by anatomic structure and detection method (autopsy or CT).

Investigation of the cervical spine: We previously published a case report on perinatally acquired spinal cord injury in a newborn child (9). PMCT, including three-dimensional reconstruction, showed dislocation of the upper cervical vertebrae. The second cervical vertebra (axis) formed a 45-degree angle with the horizontally placed first cervical vertebra (atlas), creating an abnormal gap on the posterior side of the spine.

Investigation of the sacral bone from King Canute the Saint: King Canute the Saint was killed in St. Alban Church in Odense on July 10 1086. We published a case report presenting the results of an anthropological investigation of his skeleton, with special emphasis on a peri-mortem lesion on the sacral bone (5). PMCT was for the first time used in the investigation of these historical bones. The lesion in question was a horizontal fracture on the ventral surface of the 3rd sacral vertebra, with a corresponding crack on the dorsal surface of the sacral bone (**figures 2** and **3**).

Figure 2: Horizontal fracture on the ventral surface of the 3rd sacral vertebra from King Canute the Saint.

Figure 3: The crack on the dorsal surface of the sacral bone from King Canute the Saint.

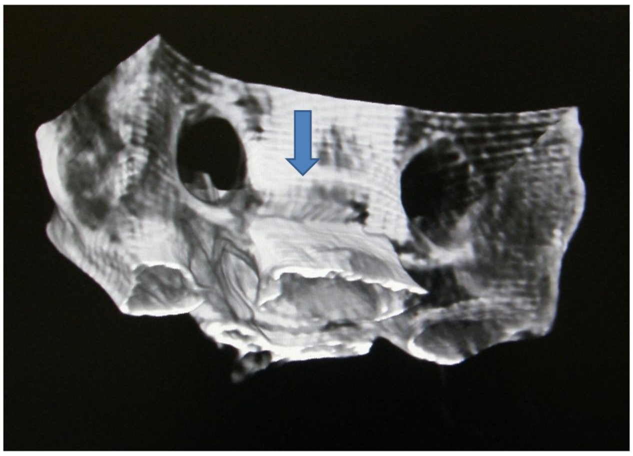

Figure 4: 3D CT scan of the sacral bone of King Canute the Saint. The infraction on the anterior surface was a so-called hinge fracture, wherein the fractured area of the lamina compacta was still partially attached to its original bone.

The fracture on the anterior side of the sacral bone was a so-called hinge fracture, where the fractured area of lamina compacta was still partially attached to its original bone such that the surfaces met at an unnatural angle, not unlike the opening of a letterbox (**figure 4**). On the dorsal surface, there was a 15-mm-long and 4-mm-wide horizontal wedge-shaped crack in the median crest at the 3rd dorsal sacral foramen, with fracture lines running in both directions from these foramina. The CT scans showed these two cracks to be connected. The fractures did not show any sign of callus formation or other bone reaction. We did not find any other lesions. There were no defence lesions on the lower arms or hands and no lesions on the ribs or iliac crest.

DISCUSSION

A combined discussion of the research questions based on all 12 papers in the thesis is presented here. Papers 12, 7, and 1 are predominantly quantitative investigations of the first 100, 250, and 900 PMCT investigations, respectively. Paper 10 addresses qualitative aspects of PMCT in general, and paper 4 addresses PMCT use in homicide cases. The case studies (9, 8, and 5) illustrate some specific uses of PMCT, namely investigation of the neck area (9), detection of radio-opaque material in the stomach from suicidal tablet ingestion (8), and anthropological investigation of historical bones (5). PMCT used for AIS scoring and ISS are investigated in paper 6, and paper 3 is an investigation of the inter-observer variation between a radiologist and a pathologist in injury diagnoses in traffic fatalities with a comparison to autopsy diagnoses. Two technical notes concerning PMCT coronary angiography are included (2, 11) because imaging of the coronary vessels presents a special challenge and has great clinical importance.

Validity

Our material is representative of forensic cases investigated at an institute of forensic medicine in Denmark, but not necessarily in other countries. Denmark has a low autopsy frequency, suicides are rarely autopsied, and the homicide rate is low (26). All PMCT images were obtained by the same CT scanner and evaluated at the same workstation independently of the autopsy, which would tend to make the results constant over time; however, it is possible that the learning curve of the forensic pathologist who evaluated the CT images resulted in some changes in diagnostic practise during the investigation period. One of our studies (3) indicated that the diagnostic validity could increase if a radiologist evaluates the CT images.

1: In how many cases can the cause of death be established by PMCT, and what characterises these cases?

The precipitous decrease in hospital autopsies in Denmark threatens the validity of the cause-of-death register. We have observed a decline in the number of forensic autopsies in Southern Denmark from 250 per year to now only 170 per year. In some countries that have low autopsy rates, PMCT is used to diagnose causes of death (27). It is therefore relevant to investigate the ability of PMCT to determine the cause of death (19).

We have found that PMCT and autopsy agreed on the cause of death in two-thirds of all cases investigated, although important differences were found between subgroups. The highest and lowest agreement was observed in cases of death due to injury and natural death, respectively, which is a pattern also observed by other researchers (28, 29).

Unenhanced PMCT can clearly visualise structures with high and low X-ray absorption, and it is therefore understandable that skeletal injuries, large haematomas, and pneumothoraces were easily detectable. Furthermore, a high proportion of cases were road traffic accidents wherein the cause of death was severe, and therefore easily identifiable, injuries. Intravascular contrast was not used, which explains why PMCT was unable to detect many pathological lesions, especially some important cardiovascular conditions, of importance to the cause of death.

We found that the cause of death was stated as unknown based on PMCT in a high proportion of cases, which most likely to some degree was caused by a conservative diagnostic approach. In clinical imaging, it is important not to overlook potentially treatable conditions, but in forensic imaging, it is more important to avoid false-positive diagnoses for legal reasons.

The ability of PMCT to correctly diagnose the cause of death has been investigated by other researchers. Weustink et al. (30) found, in an investigation of 30 deceased hospital patients based on CT and MR scanning followed by ultra-sonography-guided needle biopsies, good agreement with clinical autopsy with respect to the cause of death (77%, 23 of 30 patients). The discrepancies were caused by 4 cases of myocardial infarction, 1 case of endocarditis with heart failure, and 1 case of gastrointestinal bleeding.

Kashara et al. (27) found, in an investigation of 339 forensic cases, that the cause of death was diagnosable by PMCT in 7% of cases, by PMCT supplemented by other information in 54% of cases, and not diagnosable in 36% of cases. Their study had some limitations; specifically, cases were excluded if the cause of death could not be determined after autopsy because of lack of “organic lesions” or if poisoning caused the death. The scanning was performed with a slice thickness of 10 mm. It was not stated whether the PMCT evaluation was performed in a blinded manner, and although autopsy was said to have been used as the gold standard, no direct attempt to compare PMCT with autopsy was performed.

Paperno et al. (31) found 70% agreement on the cause of death between PMCT and autopsy in an examination of 27 forensic cases.

An investigation by Roberts et al. (32), based on 182 cases reported to the Oxford or Manchester coroner, showed a discrepancy rate of 32% between radiology and autopsy in identifying the cause of death, with a high inter-observer variation between radiologists. The radiologists indicated that autopsy was not required in 34% of the 182 cases. They found that the most common PMCT errors associated with identification of the cause of death were ischaemic heart disease, pulmonary embolism, pneumonia, and intra-abdominal lesions. They also found that the major discrepancies in the cause of death between PMCT and autopsy were reduced in cases where the radiologist had indicated that an autopsy was not necessary.

In a systematic review, Scholing et al. (33) assessed PMCT as an alternative to autopsy in trauma cases and evaluated 15 studies with 244 patients. The percentage agreement on the cause of death ranged from 46-100%.

Westphal et al. (34) investigated 29 patients who died from natural causes with PMCT and clinical autopsy and found a 64% agreement on the cause of death.

Yen et al. (35) performed a head and brain examination of 57 forensic cases with PMCT and PMMR. The cause of death was detected correctly by imaging in 19 of the 24 (79%) head trauma cases with the brain as the primary atrium mortis. In three cases (13%), the relevant findings that had been noted at autopsy were mostly found by PMCT and PMMR, with one exception each (i.e., laceration at the base of the brain, subcortical contusion at the base of the brain, and increased brain pressure). In two cases (8%), the main findings were not correctly detected using imaging methods.

2: What is the inter-method variation between autopsy and PMCT with regard to disease and injury diagnoses?

Other centres have published comparisons of PMCT or PMMR and autopsy findings in trauma fatalities (36, 37); in other subgroups, such as stillbirths (38) or natural deaths (39); or for specific purposes, such as forensic head and brain examinations (35). We previously compared PMCT with autopsy for a broad range of forensic deaths (1). An investigation of the inter-method variation between PMCT and autopsy is important regardless of whether PMCT is to be used as a substitute or as a supplement to autopsy.

We found, in accordance with other studies, a relatively high inter-method agreement between autopsy and PMCT (34, 40). The differences are, however, more interesting to study than the agreements. We soon realised that autopsy could not be considered a gold standard compared with PMCT but rather that PMCT outperformed autopsy in some areas. The diagnostic differences between PMCT and autopsy found in our investigation were described in the *result section*, and will not be repeated here. We found PMCT to be superior to autopsy in some areas, such as in diagnosing fractures, investigating areas not dissected in the autopsy, and detecting pneumothorax and other pathological gas collections, but PMCT also had some significant weaknesses, especially in the diagnosis of pathological lesions, mainly cardiovascular diseases. We also found that the interpretation of pulmonary findings was difficult. Differentiation of inner lividity, pulmonary oedema, contusions, and fluid aspiration was difficult.

Although PMCT was superior to autopsy in the evaluation of skeletal injuries, it was less suited for detecting soft tissue injuries, as also noted by Daly et al. (40) in an investigation of 21 victims of accidental blunt-force trauma by PMCT and autopsy. Like Daly et al., we found that aortic rupture was often overlooked.

Sochor et al. (41), in an investigation of 6 victims of fatal motor vehicle accidents by PMCT and autopsy, reported that although PMCT detected 28% more skeletal injuries than autopsy, it was less reliable in the detection of soft tissue injuries. They therefore recommended the use of PMCT as an adjunct to autopsy but not as a replacement.

Non-displaced cranial and rib fractures were not always visualised by PMCT. Jacobsen et al. (42) showed that the forensically important fracture systems in the cranium were, to a large extent, diagnosed on PMCT images but that difficulties remained in the diagnosis of hairline fractures.

Extra-axial haemorrhages are usually detected by PMCT; however, we found, like Anon et al. (43), that thin blood layers escape radiological detection. Yen et al. (35) performed a head and brain examination of 57 forensic cases by PMCT and PMMR. They found that the radiological methods usually failed in the detection of lesions smaller than 3 mm in diameter, whereas they were generally satisfactory in the evaluation of intracranial haemorrhage. Compared with autopsy, imaging was superior in the detection of pneumoencephalon or haemorrhage in the cerebral ventricles.

We found that although PMCT could not detect small injuries of inner organs, most life-threatening organ injuries were detected, as also found by Christe et al. (37) in an investigation of abdominal injuries in 34 cases of accidental death.

Aghayev et al. (36) performed a retrospective study of 24 cases of chest trauma that were analysed by PMCT, PMMR, and autopsy. They found that PMCT detected pneumothorax, pneumomediastinum, and soft tissue emphysema much better than autopsy. Pulmonary lacerations, contusions, and aspirations were found with a high sensitivity but a low specificity, whereas heart injuries were found with a low sensitivity but high specificity. They found that rupture of the heart atrium was more difficult to detect than rupture of the heart ventricle and that heart dislocation could be detected.

Wichmann et al. (44) compared the clinical diagnoses from PMCT and autopsy findings in 47 patients who died in intensive care settings. Of the 14 new major diagnoses, 10 were obtained by both PMCT and autopsy, and 4 were obtained only by autopsy (pulmonary embolism in 2 cases, septic arthritis of the knee in 1 case, and pulmonary alveolar proteinosis in 1 case).

Weustink et al. (30) performed an investigation of 30 deceased hospital patients with PMCT and PMMR, followed by ultrasonography-guided needle biopsy of the heart, lungs, liver, kidneys, and spleen, and compared the results with those of clinical autopsy. They found a sensitivity of 93%. The major false-negative findings were acute myocardial infarction (N=4), obstructive coronary artery disease (N=1), gastrointestinal haemorrhage (N=1), pneumonia (N=1), and endocarditis (N=1). PMCT was superior to PMMR for the detection of calcifications and pneumothoraces. PMMR was superior to PMCT for the detection of brain abnormalities and pulmonary emboli.

Kasahara et al. (27) noted that PMCT could not detect brain or brain stem contusions with small haemorrhages identified by autopsy.

Several researchers have tried to overcome the above-mentioned diagnostic limitations of PMCT. Roberts et al. (45) developed a simple method for in situ post-mortem coronary CT angiography that is sensitive in the identification of coronary heart disease in a small sample of ten non-suspicious adult deaths.

Ross et al. (46) found that PMCT angiography (PMCTA) in combination with CT-guided biopsy of the myocardium and lungs could validate the cause of death found at autopsy in 19 of 20 individuals thought to have died from acute chest diseases. PMCTA enabled the depiction of coronary artery disease and coronary thrombosis and seemed to be superior to autopsy in the evaluation of cardiac bypasses. The needle biopsy diagnoses included acute myocardial infarction, myocarditis, and pulmonary thromboembolism. One case of myocardial infarction in a papillary muscle was missed.

Coronary PMCTA on the isolated heart can enable visualisation of a greater number of vessel branches than are identifiable at autopsy (47) and may be used as an adjunct to autopsy in the assessment of coronary artery disease in select cases but is too work-intensive for routine use.

Jackowski et al. (48) demonstrated that PMMR is able to visualise and discriminate the different stages of myocardial infarction.

PMCT of the lungs is another area that may cause diagnostic problems. PMCT is performed on lungs that are not expanded, whereas clinical CT is performed with the lungs in the inspirational position. This difference may explain some of the problems PMCT has in differentiating between different types of lung pathology. The CT images of the lungs can be improved if the lungs are expanded by artificial post-mortem ventilation with a decrease in position-dependent densities.

Germerott et al. (49) investigated 5 cases that were ventilated using a mechanical ventilator with a pressure of 40 mbar via an endotracheal tube, a larynx mask, or a continuous or positive airway pressure mask. They described how the ventilation effect enabled the detection of pulmonary nodules in the lung parenchyma in two cases and an area of emphysema that became visible after ventilation in one case. Areas of atelectasis caused by pleural effusion did not disappear, and there were no cases of pneumothorax or other ventilation-induced artefacts.

Some of the limitations of unenhanced PMCT may be overcome by post-mortem angiography (50-53).

It is possible that differences in definitions and terminology between PMCT and autopsy could lead to diagnostic discrepancies. A standardisation of the interpretation and reporting of autopsy and PMCT findings and an international agreement on diagnosis coding must be encouraged.

3: Can PMCT be used as a screening tool for selecting cases for autopsy, and can PMCT in some cases substitute for autopsy?

The Institute of Forensic Medicine at the University of Southern Denmark has used PMCT since 2006 as a supplement to full autopsy. Other centres also use PMCT in combination with a partial autopsy (54) or as a screening tool (7, 55-57).

Our study could only partially answer the question because it only contained cases that were selected for autopsy and not cases that were not selected for autopsy. The latter type of case must be investigated in a separate study.

In Denmark, the medical officer of health (*embedslaegen*), who is a physician, is included in the decision-making process; however, the police authorities make the final decision regarding whether an autopsy should be performed, and they cover the expenses. This process draws upon information from a number of sources, including a police statement of the circumstances of death, photography from the scene of death, medical records, and inspection of the exterior part of the body.

Investigation of the deceased is important for many reasons, including jurisprudence, science, education, and quality control, and it is unfortunate that the number of hospital autopsies are declining in many countries (58). We have experienced a decline in the number of forensic autopsies at our institute due to budget cuts. New methods that can improve the coronial selection process or even in some cases substitute for traditional autopsy are clearly needed.

A study by Rutty et al. (59), based on questionnaires from 45 laymen and 27 pathologists, indicated that many relatives would prefer PMCT if this procedure could answer all relevant questions. In our investigation, we found it possible to select cases in which an autopsy was not needed with a relatively high accuracy. We estimated that nearly 30% of all autopsies could be substituted with PMCT if a day-to-day toxicology service were available. The majority of toxicology cases are drug addicts who have died from an overdose. Most of these cases were not suspicious, and the findings at the external examination were unremarkable, with only a few unexpected findings from autopsy or histology.

If the result of the toxicological analysis is not available before the body is released, an autopsy must always be performed. In such cases, we estimated that only 15% of autopsies could be substituted by PMCT. This group was dominated by accidental deaths, particularly road traffic accidents, where the death was typically caused by severe trauma that could easily be detected by PMCT. PMCT had a very high agreement with autopsy on the cause of death in this group. An obvious concern is the ability of PMCT to exclude natural diseases that could have contributed to the accident. We believe that a full autopsy should be required in the case of drivers of vehicles, while it should not be required for passengers.

There will be a small group in which PMCT indicates potentially lethal pathology while the real cause of death, such as a fatal pulmonary embolism or fatal gastrointestinal bleeding, is missed, resulting in misclassification of the cause of death if autopsy is omitted (60).

Jeffery et al. (61), who performed an investigation of how members of the criminal justice system in the UK viewed a PM examination report based on the circumstances of the case, scene details, external examination, and PMCT findings, concluded that the criminal justice system was not ready to accept the non-invasive autopsy approach and instead required a more substantive evidence base.

Autopsy is obviously necessary in cases where an extensive histological investigation is needed, such as cases of asbestosis exposure. It is also required in cases in which an infection is suspected. Post-mortem C-reactive protein (CRP) may be useful for identifying the need for a microbiological examination (62). Cases with an unknown cause of death, such as sudden unexpected infant death, must always be autopsied, and autopsy is mandatory by law if homicide is suspected.

4: What is the inter-observer variation in PMCT? Who should evaluate the images?

This research question was addressed in study 3. That study was the first inter-observer variability study that has been performed on injury diagnoses obtained from PMCT. It is difficult to generalise the information about inter-observer variability from a single study, and our investigation must be viewed as a contribution to a broader effort to validate PMCT.

There are important differences between clinical and forensic post-mortem radiology (63, 64). Neither movement nor radiation dose is a problem in the latter. Currently, contrast agents are not routinely used in PMCT, and internal lividity (24), post-mortem clotting (65), gas formation from decomposition (66), and intraperitoneal gas from gastromalacia (67) may cause interpretational problems. Furthermore, knowledge of forensic pathology, especially forensic traumatology, is needed for an accurate interpretation of the results. Forensic radiology can be considered a field that is between radiology and forensic pathology, and a forensic radiologist must be educated in both radiology and forensic pathology (64, 68).

Study 3 showed substantial inter-observer agreement between the radiologist and the pathologist, who independently evaluated the CT images from the traffic fatality victims (κ=0.65), but there were some important differences in observations that may be attributed to the different educational backgrounds of the two observers. As previously mentioned in the *Results* section, the radiologist diagnosed more injuries than the pathologist, especially in the spine, face, and skeletal system. The pathologist, however, diagnosed more injuries in the organs and soft tissues. The difference between the two observers was greatest when the diagnoses had a low AIS severity score. It is reassuring that the validity of the injury diagnoses was highest in injuries with a high AIS severity score because these diagnoses are the most important. This finding was not surprising because lesions with a high AIS severity score are generally more obvious than lesions with a lower score. From these results, we recommended that the pathologist consult a radiologist regarding the evaluation of CT images.

5: How much new information was obtained by the histological examination of tissue samples?

Needle biopsies may be obtained in cases where an autopsy has not been consented to.

Aghayev et al. (69) described how tissue biopsies from the brain, heart, lung, liver, spleen, kidney, and muscle tissue were obtained under PMCT fluoroscopy.

Bolliger et al. (70) examined 20 bodies by PMCT, PMCTA, and biopsy and compared the results with those obtained by autopsy, including histology. They found few discrepancies in the diagnoses obtained by the two approaches.

Filograna et al. (71) described a case where a 78-year-old woman died during insertion of a femoral prosthesis. PMCT showed bilateral opacification of the lung parenchyma. Multiple percutaneous needle biopsies revealed massive fat embolisation.

Automated, targeted biopsy of small structures is technically possible, as demonstrated by Aghayev et al. (72), and this technique reduces the exposure of the radiologist to radiation.

However, needle biopsies are small compared with the biopsies performed at autopsy, and a precise sampling of all pathological lesions is much easier at autopsy. In some cases, a more extensive sampling is needed, such as in cases of asbestosis or in cases where sectioning of the heart with extensive tissue sampling from the conduction system is needed. It is therefore relevant to determine the importance of histological examinations.

It has been argued that histology only plays a confirmatory role and does not alter the outcome of the final report (61); however, unexpected histological findings have been found in more than 20% of cases in some investigations (73).

We found that histology yielded important new information in nearly a quarter of all cases. However, this proportion was much smaller among cases where we had estimated that the autopsy could be substituted by PMCT. This result indicates that the amount of information lost if an autopsy is not performed in these cases would be relatively small.

6: Can PMCT be used for Abbreviated Injury Scale (AIS) scoring and Injury Severity Scoring (ISS) of traffic fatalities?

We compared AIS scores and ISSs obtained by routine PMCT and autopsy in traffic fatalities in study 6.

The AIS was primarily developed by trauma surgeons and radiologists, and its application to autopsy data may pose some problems (74). However, AIS is the only internationally accepted classification of injury by anatomic type and severity that provides a quantitative means by which to compare injuries. The AIS includes all degrees of injury, from minor to major, according to six severity grades: grade 1, minor; grade 2, moderate; grade 3, serious; grade 4, severe; grade 5, critical; and grade 6, unsurvivable.

Not all traffic fatalities are autopsied, and the sample under investigation was therefore not representative of all traffic fatalities in the study area, but it did illustrate a broad spectrum of fatal traffic accidents.

We found a high correlation between AIS scores obtained by PMCT and by autopsy. At our institute, a combination of the two methods is used in the post-mortem investigation of traffic accident victims, but our results indicate that if an autopsy is not possible, PMCT may be used as an acceptable alternative if the purpose of the investigation is to obtain an AIS score.

We found autopsy to be somewhat better in detecting and scoring lesions in soft tissues, ribs, and the cranium. These structures are directly inspected during autopsy. PMCT does not show the lesions with the same resolution as can be obtained with the naked eye. Non-displaced cranial and rib fractures cannot always be visualised with PMCT. PMCT did, however, perform a little better than autopsy in scoring lesions in bone structures in the facial skeleton, pelvis, and extremities, most likely because these areas are not easily accessible for dissection. PMCT was also slightly better than autopsy in scoring haemorrhages in meninges and pleural cavities and in detecting pneumothoraces. Sochor et al. (41) and Daly et al (40) found similar differences between PMCT and autopsy.

We found that a combination of PMCT and autopsy would provide the most accurate information and that either of the two methods could be used as a gold standard. To calculate κ-values, a gold standard was therefore constructed by assuming that when a difference in AIS score was found, the method, i.e., autopsy or PMCT, which yielded the highest score was correct. This was a reasonable approach, as the coding was done conservatively. If there was any question about the severity of an injury, the least severe AIS code was assigned. The gold standard thus obtained was used to calculate the κ-values. The κ-value for reproducibility of AIS scores confirmed that the agreement between the two methods was good.

The lowest κ-values (>0.6) were found for the facial skeleton, cerebellum, meninges, neck organs, lungs, kidneys, and gastrointestinal tract. In these areas, the κ-value demonstrated moderate agreement between PMCT and autopsy. For all other areas, there was substantial agreement between the two methods.

We found moderate agreement between ISS obtained with PMCT and AU (κ=0.53). Rupture of the aorta was often overlooked by PMCT, resulting in ISSs that were too low. PMCT showed a large haemothorax in all cases of aorta rupture, resulting in a high degree of suspicion of aorta rupture even if the rupture itself could not be detected. A solution could be to adapt the AIS scale so that the findings on PMCT of an otherwise unexplained haemothorax with suspicion of aorta rupture are given an ISS of 75.

It is possible that an optimised CT protocol with a narrower slice thickness in the area of the thoracic aorta in victims with haemothorax could improve the PMCT diagnosis of aortic rupture.

7: How can coronary PMCT angiography (PMCTA) be used for optimising clinical CT of the coronary arteries?

The thesis includes a technical note (2) that describes a method for PMCT coronary angiography as part of an on-going research project.

Former studies of post-mortem cardiac CT compared with histopathology have either included only the coronary arteries (47, 75, 76) or included the entire heart after removal from the body (77-79). A realistic attenuation of the X-ray beam cannot be obtained with these methods because scattered radiation from the surrounding muscles and organs is missing, and no weakening of the X-ray beams from passage through the body takes place. The result is a completely different image with an unrealistically clear visualisation of the plaque (80, 81). We attempted to avoid these problems by scanning the heart while it was in a chest phantom.

Jackowski et al. (82) investigated three human corpses using PMCTA with iodine contrast injected into the right femoral artery.

Saunders et al. (83) presented a quick, targeted in situ post-mortem cardiac angiography method using Urografin® contrast agent as positive contrast and air as negative contrast.

With a full CT angiography of a human corpse, the penetration of the radiation is similar to that in *in vivo* CT, but there are still some differences caused by the low body temperature and the presence of intravascular putrefaction gas.

Another methodological problem concerns the proper alignment of the CT images, the OCT images, and the histology sections, which is important for comparison of the images. Muscle and soft tissue will shrink during the fixation and decalcification process, and the tissue samples are obtained after the artery has been straightened. Earlier studies either did not describe the alignment (76, 82) or selected the tissue sample according to the distance from the ostium (47, 77, 84). To ensure the correct alignment between the CT images and the histopathology slices, we supplemented the primary CT scans with CT scans of the arteries after they had been separated from the heart. It was then possible to compare these CT images with the images from the first CT scan and ensure that the plaques were correctly identified in the histopathology slices.

The objective of this project was to achieve a method closely correlated with in vivo CT and clinical practice by adjusting the physical factors and the CT technique by placing the heart in a phantom, preparing the heart with a contrast mixture, returning the heart to room temperature (correct HU values), simulating ECG, and securing the alignment with OCT and histopathology. The limitations of this method are the missing movements of the heart and missing contrast in the aorta. A preliminary evaluation indicates that we have succeeded in producing a CT image quality that is closely correlated with clinical in vivo CT images.

We can conclude that this method of coronary CT angiography is the first to simulate clinical CT by placing the heart in a phantom and by using the new dual-energy CT technique. The method permits comparison with OCT and histopathology. The development of the method described here is the first step in an on-going research project. The method will be used to determine if evaluation of the coronary arteries by plaque characterisation and detection of rupture-prone plaques is possible; if they are possible, we will follow up with a clinical study.

8: How can PMCT contribute to the forensic autopsy?

We have found the routine use of PMCT before autopsy to be useful. PMCT provides a quick 3D *overview* of the body, including areas not routinely investigated, providing the pathologist with an opportunity to prepare and adjust the autopsy procedure. PMCT provides an overview of the injury patterns that are difficult to obtain by autopsy, making the identification of injury patterns characteristic of specific accident scenarios easier in, for example, traffic accidents. PMCT also provides an overview of single organs, such as the lungs, permitting, for example, the evaluation of the extent of aspiration found at autopsy (85) .

PMCT permits the *investigation of anatomic regions that are not routinely dissected* by autopsy, such as visualisation of an intraoral gunshot wound (86). Facial fractures are common in forensic pathology but are often overlooked at autopsy if the soft tissues of the face are not dissected. Fractures in the cranio-cervical region are also relatively common but are sometimes overlooked at autopsy. We diagnosed a serious congenital malalignment of the upper cervical vertebrae with medullary compression in a newborn baby (9). In that case, the condition had been diagnosed before birth, which may not always be the case, and the spinal cord is not always examined at autopsy. In such cases, PMCT will alert the pathologist of the need to perform a careful dissection of the neck area.

It is also of great advantage that PMCT depicts the anatomy *in situ*, undisturbed by dissection. We have, for example, found that a bolus in the pharynx can be visualised by PMCT. It is not always possible to determine the precise location of the bolus at autopsy because it can be dislodged during organ removal. PMCT can, in such cases, be reviewed to verify the location of the bolus, as has been demonstrated by Iino et al. (87). Other examples are cases of pressure pneumothorax or unilateral hydrothorax where the displacement of the mediastinum can be better appreciated on the CT images that during autopsy (**figure 5**). The fluid-filled ventricles in the brain of an infant with hydrocephalus are seen much better on PMCT because the brain will collapse as soon as it is removed from the cranium. PMCT can also contribute information regarding the in situ position of endotracheal tubes, chest tubes, and other medical tubes, which may be important in medical malpractice cases. PMCT allows massive cranial fractures to be viewed in situ (**figure 6**), which can be of importance in homicide cases where a comparison with a blunt weapon may be needed (44, 88, 89). The cranial fragments tend to fall apart upon dissection. **Figure 7** illustrates a cerebral haemorrhage in situ in a severely decomposed body from the very first CT scan we performed. At the autopsy, the brain was completely liquefied, and it was impossible to locate and measure the haemorrhage.

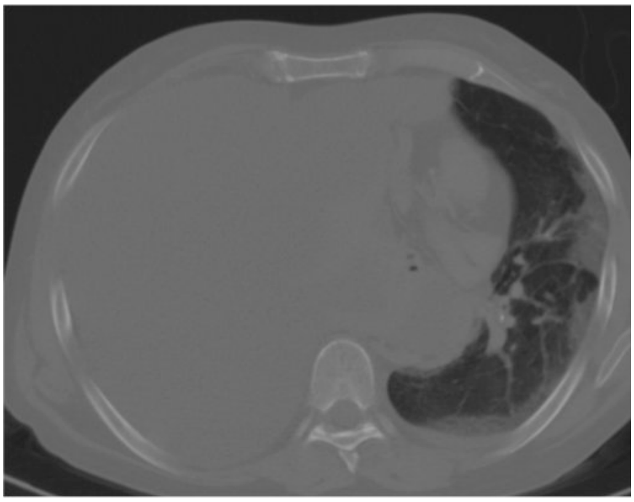

Figure 5: Unilateral hydrothorax with severe displacement of the heart in a 56-year-old woman with cirrhosis of the liver.

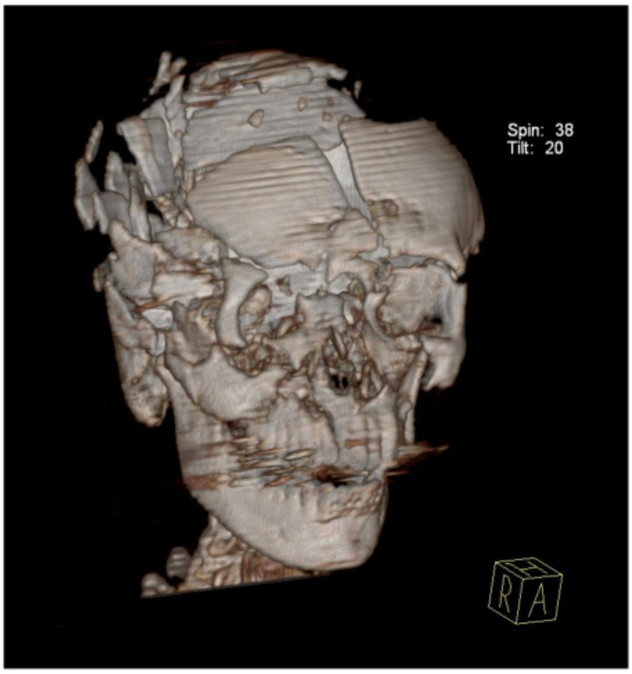

Figure 6: Severe cranial fracture in a 25-year-old car driver who suffered a frontal collision with a tree.

Figure 7: Cerebral haemorrhage in a 67-year-old man.

Figure 8: Gunshot lesion to the head in a 34-year-old man (suicide).

Structures and objects with a *high radio density* are depicted clearly on CT images, which is an advantage in gunshot cases, where the aim of the radiological examination is to locate the projectiles and fragments, to determine the bullet tracks (**figure 8**), and to evaluate the extent of damage (90, 91). Projectiles and fragments of evidential value identified by PMCT can then be recovered at autopsy. PMCT allows discrimination between foreign objects that differ in radio absorption, such as glass fragments from a shot fired through a window or metal fragments from passage through the door of a vehicle. Retrieval and analysis of such fragments may be important in reconstructing the event and in determining the location of the crime scene (92, 93).

PMCT provides *digital documentation* that is amendable to further manipulation. The volume of liquid collections in, for example, the pericardial sac (94) (**figure 9**) or pleura, can be calculated, and organ weights can be estimated (95). The digital documentation is easily stored and transmitted, thereby facilitating audit and review by others. The neutral PMCT images *reduce the need for autopsy photographs in court*.

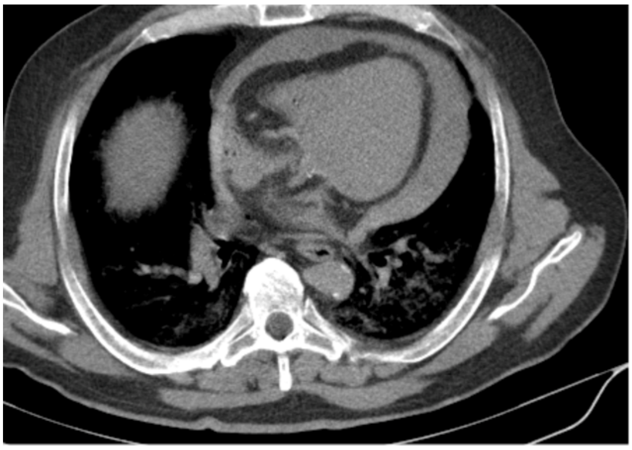

Figure 9: Haemopericardium, 56-year-old man, projectile lesion to a coronary artery.

PMCT may also be used in many types of *research projects*, some of which involve inter-disciplinary cooperation (96). We have participated in the investigation of the skeleton presumed to belong to King Canute the Saint (5), who was killed in the St. Alban Church in Odense on July 10 1086 after a six-year reign. According to the legend by clergyman Elnoth of Canterbury 20 years after the incident, the king did not try to defend himself (97). He was kneeling in prayer and was killed by a lance thrust to his side. We found a horizontal infraction on the ventral surface of the 3rd sacral vertebra and a horizontal wedge-shaped crack on the dorsal surface. The infraction on the anterior surface was a so-called hinge-fracture, where the fractured area of the lamina compacta was still partially attached to its original bone (**figure 4**). Hinging of a fracture, such as seen in this case, is considered to indicate peri-mortem trauma (98). Hinging can only occur if the bone is moist and contains organic material. Dry bone will snap off when acted on by a force sufficient to cause a break. The section of bone is bent away from the direction of the injuring force. We suggested that this infraction was caused by a thrust of a sharp instrument through the abdomen with a direction posterior and to the right (**figure 10**). This interpretation is in accordance with the interpretation given by Tkocz and Jensen (99), whereas Rasmussen et al. (97) considered this lesion to be the result of blunt-force trauma inflicted from behind. There were no other sharp lesions on the pelvis, as could have been the case if the weapon had been a sword entering the pelvic cavity through the belly. The weapon could also have been a spear, which is a

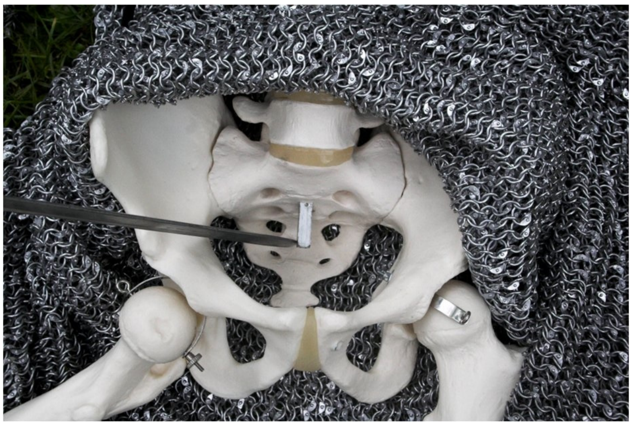

Figure 10: Reconstruction of the trauma to the sacral bone of King Canute the Saint.

likely option because the rebels were peasants who were usually armed with spears. The absence of sharp-force lesions on other bones could indicate that the king was wearing chain mail. The force of the impact must have been substantial. It seems unlikely that the king was standing up when he suffered this lesion, as a lot of the energy in the thrust would have been used to propel him backward. If, however, he had been pushed over and received the thrust while he lay on his back, more of the energy would have been transferred to the sacral bone.

PMCT is of great value in *identification* cases. Most of the relevant sections in Interpol forms can be filled out from the PMCT investigation (100), which has the additional benefit of providing a permanent objective record of the findings. Some characteristics, such as the shape of the nose or ears, may even be better appreciated from PMCT images because of their "neutral" appearance (**figure 11**).

Figure 11: 3D reconstruction of a face from PMCT data. Some characteristics, such as the shape of the nose, may be better appreciated on PMCT images because of their "neutral" appearance.

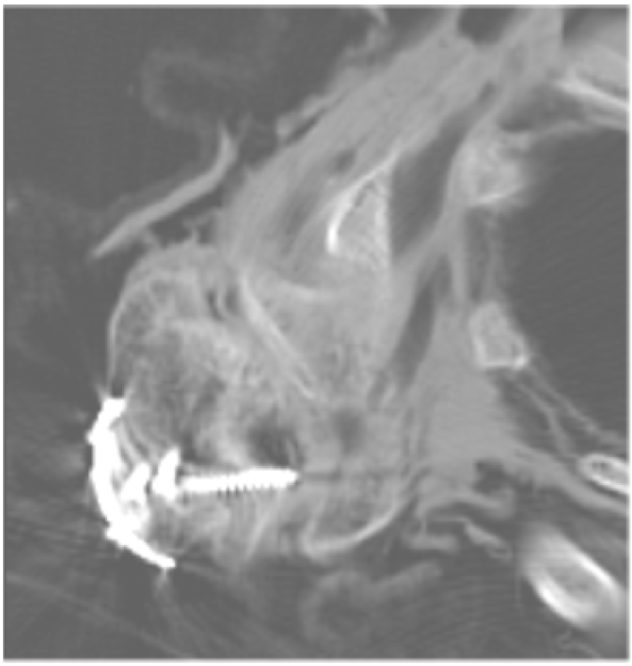

Figure 12: Shoulder implant in a 59-year-old man found dead in a ditch. Such a finding may be of importance in the identification of unknown individuals found dead.

Superimposition on portrait photographs in Photoshop is also possible. PMCT makes an anthropological assessment of the bones possible without defleshing the body (101, 102), providing information on height (from the length of the long bones), age, and sex, and may be used in computerised craniofacial reconstructions (103). Implants, such as prosthetic implants or artificial heart valves, are easily found (**figure 12**).

Sometimes, ante-mortem X-ray imaging may yield important identification clues but is often not available until after the autopsy. If a volume of digitalised X-ray information from PMCT is available, it is easy to reconstruct an X-ray image in the correct projection for comparison (104). The individual unique shape of the frontal sinus is among the features that may be used for identification based on X-ray images (105). PMCT has been used for disaster victim identification (106). In Great Britain, mobile CT units have been deployed to the autopsy area for major road traffic accidents (107, 108), and in Australia, PMCT was used with great success in the Victoria bushfire disaster (109). PMCT can substitute for the three traditionally used types of X-ray imaging: plain X-rays, fluoroscopy, and dental radiographs (110). Special software is needed for the latter.

Stab wounds are often encountered in forensic practice. Schnider et al. (111) found that PMCT could detect a high percentage of stab wounds and that it was often possible to determine the depth and direction of the wound channel. Oesterhelweg et al. (112) described a case where ante-mortem CT of stab wounds to the skull was needed for case reconstruction because the affected area of the brain had been surgically removed. Ruder et al. (113) described a case where PMCTA was needed to visualise a stab lesion to the heart. Jeffery et al. (61) found it impossible to

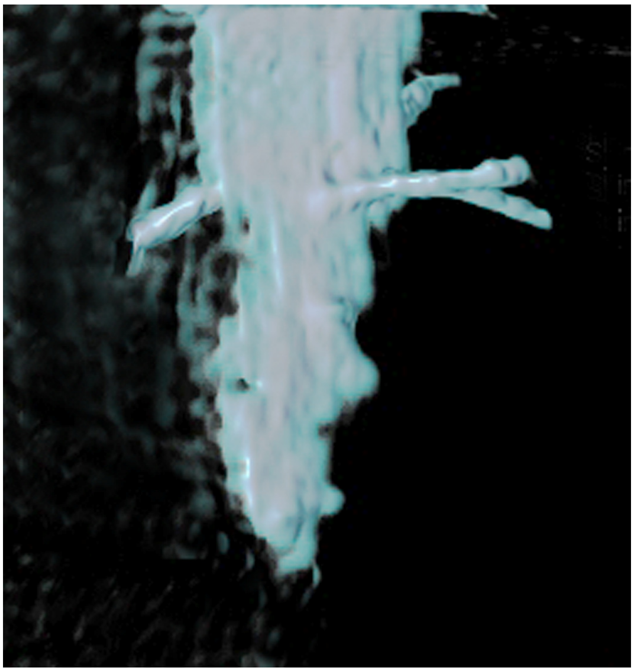

Figure 13: Contrast-filled, experimentally inflicted stab wound in liver tissue.

routinely define individual tracks, track depths, and directions, which has also been our experience (4). These problems may be overcome with scanners with better resolution or by optimising the scanning technique (111). PMCT can easily detect skeletal injuries, but not cartilaginous injuries. Both types of injury are important as indicators of thrust force. Instillation of contrast medium in the stab wound tract has been investigated experimentally (114). However, such a method would not be helpful when the wound track has traversed a natural body cavity, as this would lead to spillage of contrast medium into the cavity. We performed a study to investigate whether it was possible to obtain information about the shape of a knife blade by CT scanning of contrast-filled, experimentally inflicted stab wounds in various types of pig tissue (115). We found that a radiological evaluation of a contrast-filled stab wound in isolated tissue blocks did not permit the positive identification of the inflicting weapon; however, it was, in tissue blocks from the liver, spleen, and kidney, possible to obtain a rough idea of the shape of the inflicting knife (**figure 13**) and to differentiate a knife from a screwdriver.

Hanging, ligature strangulation, and manual strangulation are of great forensic importance. Strangulation marks on the neck are detectable by PMCT and provide a permanent record of the shape of the strangulation mark (**figure 14**). In our investigation of homicide victims, many small but important haemorrhages in the soft tissue of the neck of strangulation victims were not found by PMCT (4), as also noted by Yen et al. (116). Hyoid, thyroid, and cricoid fractures were often found, but the age of such fractures cannot be determined because haemorrhage at the fracture ends cannot be seen. Small haemorrhages in the soft tissue of the neck can, however, be detected by PMMR (116, 117). Pneumomediastinum and cervical emphysema have been described in hanging cases and are most likely a result of attempted breathing (118).

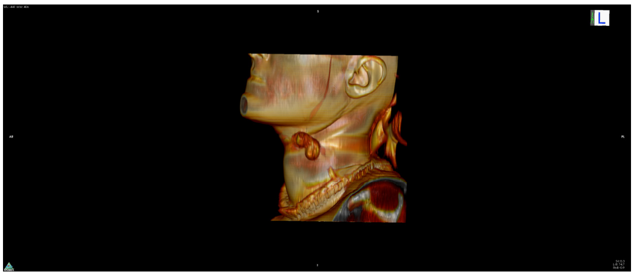

Figure 14: Hanging mark on the neck of a 35-year-old man.

Drowning: This study includes 24 drowning cases. Among the typical PMCT findings in the drowning cases was a patchy mosaic pattern of hyperdense areas in the lungs, most likely caused by aspiration of water, pleural effusions, fluid in the paranasal sinuses, fluid in the ventricle, and fluid in the main bronchi and trachea. Christe et al. (119) studied 10 freshwater drowning cases and reported similar findings. Highly attenuating material, which at autopsy turned out to be caused by aspirated sand, was found in the trachea in one of their cases. They also found that a reduced bronchial-arterial coefficient (diameter of a bronchus divided by the diameter of the accompanying pulmonary artery measured in a segmental broncho-vascular bundle of the middle lobe) was a sign of bronchospasm; that PMCT showed the diaphragmatic dome in a lower position relative to the ribs in drowning cases than in a control group, indicating enlarged lungs; and that the blood density (Hounsfield units) in the right heart chamber was reduced, indicating haemodilution. Levy et al. (120), in a study of 28 drowning cases, reported similar findings. The body fat of cadavers that have been in the water for a long time becomes transformed to an insoluble soap called adipocire. The extent of adipocire formation can be determined by PMCT and can be used to provide a crude estimate of the post-mortem interval (121).

Intoxication: We were the first group to report the finding of radio-opaque fluid in the stomach in a case of suicide by tablet ingestion (8). Aghayev et al. (122) reported three more cases. Such a finding should prompt a thorough investigation, including autopsy with toxicology (**figure 15**). Burke et al. (123) reviewed 61 cases of documented intentional therapeutic medication overdose and 61 control cases. In 31% of cases, a well-defined basal layer of radio-opaque material was clearly seen in the stomach. Only 5% of the control cases had an ill-defined increase in radiodensity toward the basal layer of the stomach, but none had a well-defined basal layer within the stomach on the axial images. The average radiodensity of the radio-opaque material was 19 HU in cases and -6 HU in controls. Other groups have reported high-density duodenal content in cases of fatal tablet ingestion (124). Therapeutic medications generally contain significantly more inert material than the active agent. These inert materials consist of diluents and binders, lubricants, and polymers. It is the presence of these various compounds that imparts the most important radiodense qualities of therapeutic medications. Iino et al. (125) described a case of a 36-year-old man who intentionally ingested mercuric chloride and died within 24 h. Post-mortem CT images showed a hyperdense “staining” of the oral, oesophageal, and gastric wall.

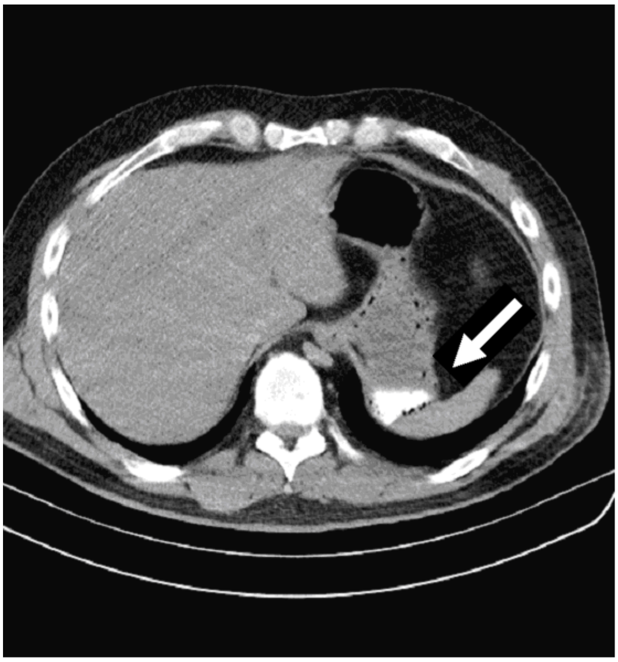

Figure 15: Transverse CT image from an adult male whose circumstances of death raised the possibility of intentional overdose. PMCT showed radio-opaque material in the stomach with an HU value of 290, and the toxicological analysis revealed a lethal concentration of codeine and salicylic acid in the blood. The radio-opacity in this case was due to magnesium hydroxide, which is a component of non-prescription medications containing codeine and acetylsalicylic, which were found at the scene of death.

Rohner et al. (126) found that urinary bladder distension on PMCT was related to intoxication, with no significant difference between urinary volume and type of drug. With a cut-off value of 330 ml, the specificity was 97% and the sensitivity was 25%.

Burnt bodies: Bodies damaged by fire must be investigated to determine the identity and to establish the cause and mode of death. It is important to determine if the deceased individual was alive when the fire started and to find injuries. PMCT is helpful in determining the identity of and detecting projectiles in victims who were shot and then torched (127). PMCT depicts the extent of burns and may be helpful in identifying spine and pelvic fractures (128). PMCT cannot detect soot in the airways, which is an important sign caused by breathing in smoke from the fire. A so-called pseudo-haematoma, which is a post-mortem epidural haematoma caused by heat, is easily identified by PMCT. It traverses the cranial suture lines, in contrast to a true epidural haematoma. PMCT is useful in determining the number of victims and obtaining an overview in cases of multiple fire deaths (109).

Areas of low radiodensity, such as air, are also clearly depicted on CT images.
PMCT is therefore well suited to detect abnormal gas collections, such as pneumothorax, pneumomediastinum, pneumoencephalon, and air embolism (**figure 16**). Air embolism may occur in various forensic settings, such as head trauma (129), diving accidents, stab wounds, gunshot wounds (130), traumatic pneumothorax, iatrogenic trauma (lung needle aspiration, lung biopsy, trans-bronchial biopsy) (131), and after cardiopulmonary resuscitation in patients with diseased lung parenchyma (132, 133). In cases of massive air embolism, heart failure may occur. Hypoxic

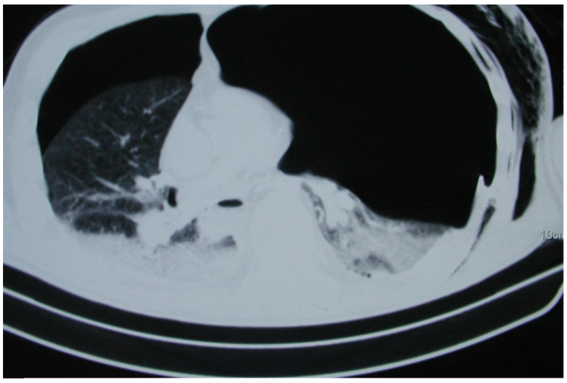

Figure 16: Pneumothorax in a 64-year-old man who was trampled by a horse.

brain death is also possible due to vascular obstruction in the cerebral vessels. Diagnosing air embolism at autopsy is difficult. One method involves aspiration of air from the right heart chamber, a method that allows for a chemical analysis of the aspirated air. Putrefaction causes the formation of gas that contains CH_4, NH_3, H_2S, CO_2, H_2, N_2, cadaverine, and putrescine. PMCT readily displays the amount and distribution of gas in the vascular system and in the cardiac chambers but does not allow for a chemical characterisation of the gas. The distribution of the gas may indicate whether the presence of gas is caused by air embolism or putrefaction. Putrefaction begins immediately after death, and gas, primarily produced by bacteria from the intestinal flora, becomes apparent on PMCT after a few hours, depending on the ambient temperature and on whether the deceased received antibiotic treatment or had a fever. The bacteria spread from the gastrointestinal tract via the portal vein to the right heart chamber, where the volume of putrefaction gas is highest, in contrast to cases of air embolism, in which the greater volume of air is in the systemic arterial circulation.

LIST OF ABBREVIATIONS

AIS: Abbreviated Injury Scale

CRP: C-reactive protein

CT: Computed tomography

ICD: International Classification of Diseases

ISS: Injury Severity Score

MIP: Maximum intensity projection

MPR: Multiplanar reconstruction

OCT: Optical coherence tomography

PMCT: Post-mortem computed tomography

PMCTA: Post-mortem computed tomography angiography

PMMR: Post-mortem magnetic resonance imaging

The abbreviations for post-mortem imaging modalities and methods are in accordance with the recommendations from an international expert group that includes the author (13).

SUMMARY

Modern diagnostic imagining techniques are gaining popularity in forensic medicine. Denmark has been involved in the development of this use of imaging techniques from the beginning. The Institute of Forensic Medicine at the University of Southern Denmark acquired a helical computed tomography (CT) scanner in 2006. This thesis presents our research on post-mortem CT (PMCT) and addresses the following research questions:

1. In how many cases can the cause of death be established by PMCT, and what characterises these cases?
2. What is the inter-method variation between autopsy and PMCT with regard to disease and injury diagnoses?
3. Can PMCT be used as a screening tool for selecting cases for autopsy, and can PMCT in some cases substitute for autopsy?
4. What is the inter-observer variation in PMCT? Who should evaluate the images?
5. How much new information is obtained by the histological examination of tissue samples?
6. Can PMCT be used for Abbreviated Injury Scale (AIS) scoring and Injury Severity Scoring (ISS) of traffic fatalities?
7. How can coronary PMCT angiography (PMCTA) be used for optimising clinical CT of the coronary arteries?
8. How can PMCT contribute to forensic autopsies?

Materials and methods:
This thesis investigated 900 forensic cases that were CT-scanned and autopsied at the Institute of Forensic Medicine, University of Southern Denmark, from 2006-2011. The scanner was a Siemens Somatom Spirit dual-slice CT-scanner with a Siemens Syngo MultiModality workstation. Contrast enhancement was not used. Autopsies were performed according to the Danish government's official guidelines. PMCT and autopsy findings were interpreted independent of each other. Diagnoses, including the cause of death and histology findings, were registered in a computer database (SPSS) together with information about the deceased and the case. We also estimated whether an autopsy could have been omitted according to a set of predetermined criteria.

Results:
1. Cause of death: Agreement about the cause of death was found in 66 % of cases. No cause of death could be found by PMCT in 45% of cases, compared with only 15% of cases by autopsy. The agreement between PMCT and autopsy was highest in cases of accidents (85%) and lowest in cases of natural deaths (48%).

2. Inter-method agreement: A total of 70% of non-injury diagnoses and 65% of injury diagnoses were obtained by both autopsy and PMCT. PMCT was unable to detect some important non-injury diagnoses (coronary stenosis, coronary thrombosis, acute myocardial infarction, fibrotic myocardial scar, pulmonary embolism, oesophageal varices, and non-perforated gastrointestinal ulcerations). PMCT was good at detecting major haemorrhages, air and fluid collections, fatty liver, hyper- and hypotrophy, neoplasms, cysts, gallstones, kidney stones, aneurysms, and cerebral haemorrhages. PMCT was superior to autopsy in detecting fractures in the facial skeleton, spine, and extremities, but it was less reliable in detecting injuries in the inner organs, small haematomas, and aortic transections.

3. PMCT as a screening tool: It was estimated that PMCT could substitute for autopsy in at least 15% of cases, but in 6% of these cases, an important autopsy finding would be missed. There were more accidents and fewer natural deaths among the cases where an autopsy could be omitted.

4. Inter-observer variation: The inter-observer variation of PMCT injury diagnoses between a forensic pathologist and a radiologist was evaluated in a study of 67 traffic fatality victims with 994 AIS injury diagnoses. The study showed a substantial inter-observer agreement (κ=0.65). The radiologist diagnosed more injuries than the pathologist, especially injuries in the spine and face. The radiologist diagnosed more injuries in the skeletal system, and the pathologist diagnosed more injuries in the organs and soft tissues. The difference between the two observers was smallest for lesions with a high AIS severity score.

5. Importance of histology: The histological examination confirmed the autopsy findings in 59% of all cases. Important new information was obtained in 23% of cases, and some, but less important, new information was obtained in 15% of cases. There were significantly fewer important microscopic findings (7%) in cases where it had been estimated that an autopsy could be substituted by PMCT.

6. PMCT used to assess the Abbreviated Injury Scale (AIS) score and Injury Severity Score (ISS): This question was investigated in a study of 52 traffic fatalities. On average, there was 94% agreement between PMCT and autopsy in the detection of lesions, with κ-values varying from 0.39 to 1.00 among the different AIS anatomical regions. When different severity scores were obtained, PMCT detected more lesions with a high severity score in the facial skeleton, pelvis, and extremities, whereas autopsy detected more lesions with high scores in soft tissues, the cranium, and ribs. In 85% of these traffic fatalities, there was no or moderate variation in the ISS (κ=0.53). When the difference was higher, it was usually because an aortic rupture had been overlooked by PMCT.

7. *Post-mortem coronary angiography:* A new method was presented in which an autopsy heart was investigated with optical coherence tomography (OCT) and scanned in a chest phantom with dual-energy CT. A contrast agent that solidified after cooling was injected into the coronary arteries. The OCT and CT images were compared with their corresponding histological sections. A procedure for ensuring the correct alignment of the images was also developed.

8. Contribution of PMCT to forensic autopsy: PMCT findings in cases of fire, identifications, traffic fatalities, drowning, bolus deaths, and homicides are presented. Three case studies are summarised: detection of tablet residues in the stomach, detection of a congenital displacement of the second cervical vertebra in a newborn, and an investigation of the sacral bone from the mediaeval Danish king Canute the Saint.

Discussion:
1. Cause of death: Unenhanced PMCT could not detect several important natural causes of death, including many cardiovascular diseases, but could identify the cause of death in many cases where death was caused by injury, most likely because fractures, large haemorrhages, and pneumothoraces could be detected by

PMCT relatively easily and because many deaths were caused by severe, and therefore easily identifiable, injuries.

2. Inter-method variation: PMCT was superior to autopsy in some cases, such as in diagnosing fractures, investigating areas not dissected in the autopsy, and detecting pneumothorax and other pathological gas collections, but PMCT also had some significant weaknesses, especially in the diagnosis of pathological lesions (mainly cardiovascular diseases). Several researchers have suggested strategies to overcome these diagnostic limitations, including the use of CT-guided biopsy and post-mortem angiography.

3. PMCT as a screening tool: It was possible to select some cases in which PMCT could replace autopsy. Our study included only cases selected for autopsy and should be supplemented with a study on cases not selected for autopsy. Autopsy must always be performed in some cases, e.g., if an extensive histological investigation is needed or in automobile drivers to exclude natural diseases that may have caused the accident. Autopsy is mandatory by Danish law if homicide is suspected.

4. Inter-observer variation: The inter-observer variation was low, but the radiologist diagnosed more injuries than the pathologist. It is recommended that the pathologist consult a radiologist for the evaluation of CT images.

5. Importance of histology: The importance of histology and the possibility to supplement PMCT with needle biopsies were discussed.

6. PMCT used for Abbreviated Injury Scale (AIS) scoring and for assessment of the Injury Severity Score (ISS): We found a high correlation between AIS scores obtained by autopsy and PMCT. Autopsy was best for AIS scoring of soft tissues, the cranium, and ribs, while PMCT was best for AIS scoring of the facial skeleton, pelvis, and extremities. There was moderate agreement between ISS obtained with autopsy and PMCT. Rupture of the aorta was often overlooked by PMCT, resulting in ISSs that were too low. A combination of autopsy and PMCT provided the most accurate information.

7. *Post-mortem coronary angiography:* The method presented can be used to determine whether CT evaluation of the coronary arteries with plaque characterisation is possible in preparation for a clinical study.

8. The contribution of PMCT to forensic autopsy: PMCT permits investigation of anatomic regions that are not routinely dissected by autopsy and depicts the anatomy in situ. PMCT provides digital documentation that is easily stored and transmitted, thereby facilitating audit and review by others, and provides images that are more aesthetically suited for court presentation than autopsy photographs. The importance of PMCT in gunshot cases, identifications, stab wounds, strangulation, drowning, intoxications, fire deaths, and pathological gas collections was discussed. The CT investigation of the bones belonging to King Canute the Saint was discussed.

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