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REVIEW

Relevant findings on postmortem CT and postmortem MRI in hanging, ligature strangulation and manual strangulation and their additional value compared to autopsy – a systematic review

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Abstract

Several articles have described the use of postmortem computed tomography (CT) and postmortem magnetic resonance imaging (MRI) in forensic medicine. Although access to CT scanners and, particularly, access to MRI scanners, is still limited for several institutes, both modalities are being applied with increasing frequency in the forensic setting. Certainly, postmortem imaging can provide crucial information prior to autopsy, and this method has even been considered a replacement to autopsy in selected cases by some forensic institutes. However, the role of postmortem imaging has to be assessed individually according to various injury categories and causes of death. Therefore, this systematic review focuses on the role of postmortem CT and MRI in cases of hanging and ligature and manual strangulation. We assessed the most common and relevant findings on CT and MRI in cases of strangulation and compared the detectability of these findings among CT, MRI and autopsy. According to the available literature, mainly fractures of the hyoid bone or thyroid cartilage were investigated using postmortem CT. Compared to autopsy, CT demonstrated equivalent results concerning the detection of these fractures. A currently described "gas bubble sign" may even facilitate the detection of laryngeal fractures on CT. Regarding the detection of hemorrhages in the soft tissue of the neck, postmortem MRI is more suitable for the detection of this "vital sign" in strangulation. Compared to autopsy, postmortem MRI is almost equally accurate for the detection of hemorrhages in the neck. Another "vital sign", gas within the soft tissue in hanging, which is hardly detectable by conventional autopsy, can be clearly depicted by CT and MRI. The number of cases of manual and ligature strangulation that were investigated by means of postmortem CT and MRI is much smaller than the number of cases of hanging that were investigated by CT and MRI. Likewise, judicial hanging and the hangman's fracture on postmortem imaging were described in only a few cases. Based on the results of this systematic review, we discuss the additional value of CT and MRI in fatal strangulation compared to autopsy, and we reflect on where the literature is currently lacking.

Keywords Hanging · Strangulation · Postmortem CT · Postmortem MRI · Hyoid and thyroid fracture · Vital reaction

Introduction

According to forensic pathology [1, 2] the term "strangulation" describes a form of asphyxia, in which external pressure to the neck compresses airways and blood vessels. In the case of a fatal outcome, the cause of death is cerebral hypoxia secondary to compression of brain-supplying vessels. Strangulation is divided into three forms, namely ligature strangulation, manual strangulation, and hanging, according to its mechanism. Ligature strangulation describes the use of any kind of material tightened around the neck, whereas manual strangulation describes when the offender uses his/her own hand, arm (chokehold) or leg to put pressure on the neck. Both ligature and manual strangulation describe pressure to the neck by force other than from body weight of the strangled person. If the body weight of a strangled person is involved in the mechanism of strangulation, it is described as hanging. Hanging is termed incomplete if parts of the body touch the ground, whereas a free-hanging body is described as a complete suspension. In all three forms of strangulation, common

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findings at autopsy are fractures of the hyoid bone and/or the thyroid cartilage, as well as hemorrhages in the soft tissue of the neck. The detection of fractures and lesions allows assessment of the extent and mechanism of the sustained injuries. Further, soft tissue hemorrhages are considered evidence of vitality, which is important for the reconstruction of the sequence of events [3].

As a supplement to autopsy, postmortem computed tomography (CT) is used in order to detect pathologies, injuries, fractures and foreign bodies [4–6]. In the case of soft tissue lesions, magnetic resonance imaging (MRI), which has been found to have applications in forensic and postmortem settings, is preferred [7]. In this systematic review, we investigated the performance of postmortem CT and MRI in fatal strangulation cases according to the available literature.

The objectives of this systematic review were as follows:

1). Provide an overview of the current literature on postmortem CT and MRI in hanging, ligature strangulation and manual strangulation.
2). Summarize the most common and relevant findings of CT and MRI.
3). Compare the detectability of findings of CT, of MRI and at autopsy.
4). Discuss the value of CT and MRI in fatal strangulation.
5). Reflect on where the literature is currently lacking.

Methods

A literature search was carried out for articles in English that describe the use of postmortem CT and/or MRI in cases of strangulation. The literature review was performed in PubMed using the following terms:

1). Postmortem CT strangulation.
2). Postmortem CT hanging.
3). Postmortem MRI strangulation.
4). Postmortem MRI hanging.
5). Forensic imaging strangulation.
6). Forensic imaging hanging.
7). Forensic radiology strangulation.
8). Forensic radiology hanging.

Two reviewers independently evaluated the articles that were found to evaluate their suitability for inclusion in this review.

Articles were excluded according to the following exclusion criteria:

1). No postmortem CT or MRI of the neck region was performed.
2). The findings could not be assigned to strangulation deaths.
3). Postmortem CT or MRI was performed on removed tissue.
4). Description of one selected case (case reports).

Additionally, Google Scholar was used to reveal further non-PubMed-listed articles. Due to the large number of results on Google Scholar, only the abstracts of the first 100 results of each search term were briefly reviewed. Articles were excluded according to the aforementioned exclusion criteria.

All authors have read the included articles. The Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2 [8]) tool was used to assess the quality of the included articles and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA [9]) guidelines were taken into account.

Results

The PubMed search revealed 138 publications (Fig. 1). After reviewing the abstracts, 115 articles were excluded, as neither postmortem CT nor postmortem MRI was performed. From the remaining articles, three articles [10–12] had to be excluded, as the findings could not be solely assigned to strangulation-related deaths. Additionally, three articles had to be excluded as CT [13] or microfocus CT (μCT) [14, 15] was performed on removed tissue. Finally, six case reports [16–21] were excluded. The remaining 11 articles demonstrated and discussed the use of postmortem radiology in strangulation cases. One small case series [22] was published in 1994 and described CT and MRI findings in two cases of judicial hangings. Five articles [23–27] were published in the first decade of the new millennium. Four of these articles investigated a small number of cases using postmortem CT ($n = 2$ [23], $n = 5$ [24], $n = 9$ [25], and $n = 8$ [26]), and three of them additionally performed postmortem MRI [23–25]. The remaining article described the use of postmortem MRI and videolaryngoscopy after hanging [27]. Five articles [28–32] were also published after 2010 that exclusively presented CT findings ($n = 11$ [28], $n = 32$ [29], $n = 25$ [30], $n = 35$ [31], and $n = 14$ [32]).

Google Scholar revealed an additional abstract regarding postmortem CT findings in the context of hanging that was related to the 3rd Congress of the International Society of Forensic Radiology and Imaging [33]. The number of cases ($n = 47$) and the extent of their findings are clearly described in this abstract; thus, the CT and autopsy findings were included in this review.

The QUADAS-2 checklist revealed that all articles, which compared radiological with autopsy findings, were potentially biased and the level of detail of data varied widely. In almost

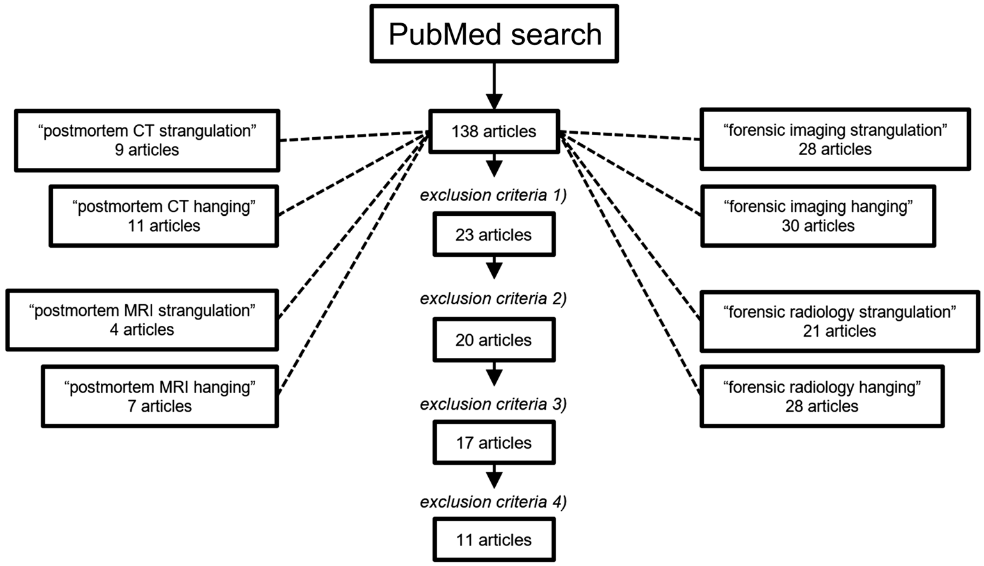

Fig. 1 A PubMed search yielded 138 articles. According to the exclusion criteria, 11 articles remained for this systematic review. The Google Scholar search revealed an additional abstract that was related to the 3rd Congress of the International Society of Forensic Radiology and Imaging. This abstract was included, as it clearly describes the amount of PMCT findings in hanging

all studies it was unclear if the forensic pathologist performing the autopsy was blinded to whether CT or MRI findings had been detected.

Three publications investigated cases of strangulation among several other causes of death [23, 28, 30]. All articles described findings in the context of hanging except Decker et al. [32], who focused solely on manual and ligature strangulations. Yen et al. [25] discussed four cases of manual strangulation and Kempter et al. [26] two cases of ligature strangulation in addition to their cases of hanging. All but three articles [23, 28, 30] indicated the number of incomplete and complete hangings. However, apart from Kempter et al. [26], none of the articles described the findings separately in relation to complete or incomplete hanging.

The manner of death was accidental in four cases (manual or ligature strangulation: $n = 3$ [32]; autoerotic hanging: $n = 1$ [26]); homicide in 15 cases (manual or literature strangulation: $n = 15$ [25, 26, 32]) and suicide in 86 cases (hanging: $n = 84$ [23, 25–27, 29, 31]; ligature strangulation: $n = 2$ [32]). Wallace et al. [22] investigated judicial hanging (n = 2) exclusively. The remaining four articles [24, 28, 30, 33] did not mention the manner of death.

Judicial hangings and the hangman's fracture

Wallace et al. [22] described postmortem CT and MRI findings in two cases of judicial hanging. The first case, which involved a knot below the ear (termed subaural), demonstrated a cervical spine ligamentous injury and a partial disruption of the vertebral arteries. The second case, which involved a knot below the chin (termed submental), displayed a complete cervical spine ligamentous disruption and a complete cord transection. Both cases displayed fractures of the transverse processes. Diffuse subarachnoid hemorrhages were detected on postmortem CT and MRI of the head.

Hayashi et al. [29] focused on the occurrence of the hangman's fracture in nonjudicial hanging and its detection on postmortem CT. In 32 adult hanging deaths (complete: $n = 4$; incomplete: $n = 28$), one case displayed a hangman's fracture. A man of approximately 100 kg jumped from a bridge with a rope 3.1 m in length and a thickness of 2.2 cm looped once around his neck. This case also displayed fractures of the hyoid bone and thyroid cartilage. The remaining 31 cases were not described in detail and no findings other than presence or absence of a hangman's fractures were reported by the authors.

Hyoid and laryngeal fractures

The number of cases that demonstrated a hyoid or thyroid fracture on postmortem CT compared to at autopsy are listed in Table 1. In hanging ($n = 106$), hyoid ($n = 26$) or thyroid fractures ($n = 25$) were almost equally detected as often as on postmortem CT. Autopsy demonstrated less hyoid ($n = 23$) than thyroid fractures (n = 26). In three cases, autopsy could not confirm CT findings of hyoid fractures. In contrast, CT missed one thyroid fracture compared to autopsy. Blanc-Louvry et al. [28] did not detect any thyroid fractures in 11 cases, neither on CT nor at autopsy. Kempter et al. [26] and Schulze et al. [31] detected more thyroid ($n = 4$ [26]; $n = 19$ [31]) than hyoid fractures ($n = 2$ [26] $n = 11$ [31]), in contrast to all other articles that detected equal or more hyoid than thyroid fractures on CT and at autopsy. Considering the number of investigated cases per article, Elifritz et al. [33] detected substantially fewer fractures per cases than all other articles. Schulze at al. [31] mentioned that autopsy was not blinded to the CT findings, and several fractures at autopsy were only detected after a second assessment. A dehiscence of the

Table 1 Fractures and hemorrhages detected on postmortem CT compared to those detected at autopsy

			Fracture of the hyoid bone		Fracture of the thyroid cartilage		Soft tissue hemorrhage	
		NoC	CT	AUT	CT	AUT	CT	AUT
2003	Thali et al. [23]	2	2	2	1	1	0	2
2005	Yen et al. [25]	5	3	2	1	1	4	4
2009	Kempter et al. [26]	6	2	2	4	3	0	4
2013	Blanc-Louvry et al. [28]	11	5	6	0	0	2	11
2013	Elifritz et al. [33]	47	3	0	0	2	2	3
2018	Schulze et al. [31]	35	11	11	19	19	*n.m.*	*n.m.*
Overall hanging*		106	26	23	25	26	8	24
2009	Kempter et al. [26]	2	1	1	2	2	1	2
2018	Decker et al. [32]	10	1	0	2	1	1	3
Overall ligature strangulation		12	2	1	4	3	2	5
2005	Yen et al. [25]	4	1	1	1	1	4	4
2018	Decker et al. [32]	2	1	1	1	1	1	1
Overall manual strangulation		6	2	2	2	2	5	5
Overall**		124	30	26	31	31	15	34
%			24.2	21.0	25.0	25.0	16.9	38.2

NoC number of cases, *CT* computed tomography, *AUT* autopsy, *n.m.* not mentioned

Overall, a hyoid fracture was detected slightly more often on postmortem CT (24.2%, 30/124 cases) than at autopsy (21.0%, 26/124 cases). Thyroid fractures were detected equally as often on CT and at autopsy (25.0%, 31/124 cases). However, CT detected much less hemorrhages (16.9%, 15/89 cases) than autopsy (38.2%, 34/89 cases). Schulze et al. [31] did not focus on the detection of hemorrhages by CT; therefore, this article and its 35 cases had to be excluded in regard to hemorrhages (*overall hanging: NoC = 71; **overall: NoC = 89). The article by Wallace et al. [22] who investigated judicial hanging, was also excluded from this table. Aghayev et al. [24] and Hayashi et al. [29] could not be taken into account, as neither described the presence or absence of hyoid and/or thyroid fractures, except for one with a hangman's fracture. Naimo et al. [30] had to be excluded, as the findings on postmortem CT ($n = 25$; hyoid fracture: n = 2; thyroid fracture $n = 9$) were not compared to autopsy. Two cases from Decker et al. [32] had to be excluded, as the method of strangulation (manual or ligature strangulation) was unknown

arytenoid cartilage was detected only on CT in two cases. In ligature strangulation ($n = 12$), hyoid fractures ($n = 2$) were detected less often than thyroid fractures ($n = 4$) on postmortem CT. Autopsy also detected less hyoid (n = 1) than thyroid fractures ($n = 3$) but could not confirm the CT findings of one hyoid and one thyroid fracture. Additionally, a fracture of the ventrolateral arch of the cricoid cartilage that was not detected at autopsy was identified on CT by Kempter at al. [26]. In manual strangulation ($n = 6$), hyoid ($n = 2$) and thyroid fractures (n = 2) were detected equally as often on CT. Autopsy confirmed the CT findings of hyoid and thyroid fractures.

The detection of hyoid and thyroid fractures on postmortem MRI compared to that at autopsy are listed in Table 2. In hanging ($n = 12$), postmortem MRI did not demonstrate fractures of the hyoid bone or thyroid cartilage at all; however, autopsy revealed hyoid ($n = 5$) and thyroid fractures ($n = 2$). Postmortem MRI was not performed in cases of ligature strangulation. Yen et al. [25] presented four cases of manual strangulation that underwent postmortem MRI. Two cases were combined with chokeholds and the other two with blunt force by kicking. Postmortem MRI detected a hyoid and a thyroid fracture, which were both confirmed by autopsy.

Gas bubble sign

Apart from hyoid and thyroid fractures, the detection of a so-called "gas bubble sign" that is related to fractures was described by Schulze et al. [31]. The authors hypothesized that this vacuum phenomenon occurs because enclosed tissue space will expand after an external impact (rebound phenomenon). Thus, the volume within the enclosed tissue space increases, which causes a decrease in pressure. This condition allows gas to leak and forms small gas bubbles, which are potentially visible on CT. The researchers reviewed postmortem CT scans of 35 hanging deaths and 35 control deaths resulting from cardiac arrest or intoxication. A sensitivity of 79.2% and a specificity of 90.9% was calculated for the bubble-like occurrence of gas with regard to laryngeal fractures. None of the control cases displayed the gas bubbles or demonstrated any fractures. Autopsy was not able to depict the "gas bubble sign" at all.

Soft tissue hemorrhages

Postmortem CT missed several hemorrhages compared to autopsy (Table 1). In hanging ($n = 89$), autopsy revealed three

Table 2 Fractures and hemorrhages detected on postmortem MRI compared to those detected at autopsy

		NoC	Fracture of the hyoid bone		Fracture of the thyroid cartilage		Soft tissue hemorrhage	
			MRI	AUT	MRI	AUT	MRI	AUT
2003	Thali et al. [23]	2	0	2	0	1	1	2
2005	Yen et al. [25]	5	0	2	0	1	4	4
2009	Duband et al. [27]	5	0	1	0	0	4	4
Overall hanging		12	0	5	0	2	9	10
2005	Yen et al. [25]	4	1	1	1	1	4	4
Overall manual strangulation		4	1	1	1	1	4	4
Overall		16	1	6	1	3	13	14
%			6.3	37.5	6.3	18.8	81.3	87.5

NoC number of cases, *MRI* magnetic resonance imaging, *AUT* autopsy

Postmortem MRI detected much less hyoid (6.3%, 1/16 cases) and thyroid fractures (6.3%, 1/16 cases) than autopsy (hyoid fractures: 37.5%, 6/16 cases; thyroid fractures: 18.8%, 3/16 cases. Concerning the detection of hemorrhages, postmortem MRI (81.3%, 13/16 cases) was almost equal to autopsy (87.5%, 14/16 cases)

times more hemorrhages ($n = 24$) than CT (n = 8). In ligature strangulation ($n = 12$), autopsy also detected more than twice as many hemorrhages ($n = 5$) than CT (n = 2). In contrast, in manual strangulation ($n = 6$), hemorrhages were detected equally as often on CT (n = 5) and at autopsy (n = 5). All four cases of manual strangulation from Yen et al. [25] demonstrated hemorrhages on CT, on MRI and at autopsy.

Soft tissue hemorrhages were detected almost equally as often on postmortem MRI and at autopsy (Table 2). In hanging ($n = 12$), a single hemorrhage (n = 1) was missed by postmortem MRI. In manual strangulation ($n = 4$), postmortem MRI and autopsy detected hemorrhages in all cases.

Gas within the soft tissue

Two articles investigated the occurrence of gas accumulations in the soft tissue. Aghayev et al. [24] focused on the presence of pneumomediastinum and soft tissue emphysema in hanging. It was assumed that, due to the increased intra-alveolar pressure in hanging, ruptures of the marginal pulmonary alveoli can occur, and the air may ascend along the bronchi to the mediastinum and the subcutaneous space of the neck, which may serve as evidence for vitality. The authors described the use of postmortem CT and MRI. Three of five cases displayed gas accumulations in the soft tissue of the neck and the mediastinum using postmortem CT. Autopsy was able to infer the occurrence of gas in the soft tissue in only one case due to a “cracking noise” during dissection. Elifritz et al. [33] investigated 47 cases of hanging deaths, of which 12 cases displayed subcutaneous gas in the neck and/or the head disproportionate to decomposition. These gas accumulations were not detected at autopsy. Elifritz et al. [33] detected subcutaneous gas ($n =$ 12, only on CT) more often than hyoid ($n = 3$, only on CT) and thyroid fractures ($n = 2$, only at autopsy). According to both articles, 28.8% of the 52 hanging cases demonstrated accumulation of gas in the soft tissue (Table 3).

Discussion

This systematic review provides a detailed overview of the current literature concerning postmortem CT and MRI in the contexts of hanging, ligature strangulation and manual strangulation. Despite concerns regarding the quality of the reviewed articles, the literature revealed that postmortem CT and MRI might have a certain potential for the detection of strangulation-related findings. Most of the articles presented cases of hanging. Only a few articles investigated cases of ligature and manual strangulation; thus, the number of reported cases was small. The results of postmortem MRI in manual strangulation cases were narrative, as these results were derived from one single article. The literature review did not

Table 3 Gas within the soft tissue in hanging detected on postmortem CT compared to those detected at autopsy

		NoC	Gas within the soft tissue	
			CT	AUT
2005	Aghayev et al. [24]	5	3	1
2013	Elifritz et al. [33]	47	12	0
overall		52	15	1
%			28.8	1.9

NoC number of cases, *CT* computed tomography, *AUT* autopsy

In hanging, gas within the soft tissue occurred in more than one-fourth (n = 15) of all cases ($n = 52$). Aghayev et al. additionally performed and detected gas in the soft tissue on postmortem MRI. So far, neither postmortem CT nor postmortem MRI has been used to investigate this “vital sign” in ligature or manual strangulation reveal any articles regarding ligature strangulation on postmortem MRI. Limited accessibility to MRI scanners may be the main reason for the small number of strangulation cases that underwent postmortem MRI. Additionally, time constraints may lead to a reluctance in performing time-consuming MRI examinations.

As expected, the hanging deaths were almost exclusively due to suicide; in turn, the ligature and manual strangulation cases were mainly associated with homicide. Hanging, in addition to intoxication and firearms, is a common method used to commit suicide [11]. Homicidal and accidental (mostly autoerotic) hanging have rarely been described. In contrast, ligature strangulation is rarely suicide-related, and suicide by manual strangulation is even considered infeasible [1].

In two cases, the CT and MRI findings of judicial hanging were described. In judicial hangings, a slipknot is placed around the neck of the convict, and after the executioner pulls the lever, the body drops through a trap door. In such hanging scenarios, the form of neck injury is not only affected by the weight of the body itself and the position of the knot but also by the distance of the drop. At the abrupt end of the body's drop, the head is jerked backward, which can cause a typical cervical spine fracture, namely, the hangman's fracture [1, 34]. This type of fracture is also frequently detected in traffic accidents [35]. This fracture can also occur in nonjudicial hanging when the drop exceeds a certain length, for example by hanging from a bridge as described by Hayashi et al. [29]. Hanging from a bridge can also even lead to complete decapitation [36–39].

Most of the articles demonstrated the detection of hyoid or thyroid fractures in cases of hanging. The percentage of hyoid or thyroid fractures in hanging varies widely in the literature [40]. The prevalence of fractures increases at advanced ages [41], a finding that was also demonstrated by Schulze et al. [31]. At younger ages, in turn, the hyoid bone is more flexible [31]. But the position of the knot plays a role, as an anterior knot position is unlikely to cause a hyoid or thyroid fracture compared to other knot positions [11]. Additionally, fractures of the hyoid bone or thyroid cartilage can also occur postmortem [42] and healed fractures are commonly encountered at autopsy [43]. While histological examinations in addition to autopsy will allow for assessing the age of a fracture, the distinction between a healed and a recent fracture on CT (or MRI) is more challenging. Characteristics of posttraumatic sequelae are pseudarthrosis or callus formation in the course of bone remodeling [44]. The detection of a callus enables the identification of a healed fracture on CT. Pseudarthrosis can be distinguished from a recent fracture by its rounded and sclerotic (thus CT hyperdense) borders, whereas sharply delineated borders suggest a recent fracture [44]. Nevertheless, pseudarthrosis is difficult to distinguish from a recent fracture on CT, which can be considered a limitation of postmortem CT for detecting laryngeal and hyoid fractures in hanging, ligature strangulation and manual strangulation that deserves mentioning. Bleedings in the soft tissue within close proximity to the fracture are diagnostic signs for a recent fracture; however, bleedings in the soft tissue are not always detectable, especially on CT compared to MRI and autopsy.

Postmortem MRI showed poor results regarding the detection of fractures compared to postmortem CT and autopsy. On CT and at autopsy, thyroid fractures were detected almost equally as often, but CT detected even more hyoid fractures than autopsy did. This may be due to either anatomical variations or deviations of the hyoid bone that were erroneously interpreted as fractures on CT, or be because CT is indeed more suitable than autopsy for the detection of tiny fractures. Grabherr et al. [45] chose the depiction of a displaced bilateral fracture of the cricoid cartilage in a case of strangulation to demonstrate the advantage of CT concerning the detection of bone lesions that are difficult to deduct at autopsy and described this finding as evidence for the application of relevant force to the neck. Graziani et al. [12], in turn, stated that autopsy shows clear advantages over CT regarding the detection of hyoid or laryngeal fractures in cases of strangulation, but CT and autopsy both showed a high concordance for the detection of laryngeal and hyoid fractures in cases that involved major trauma to the neck. The detection of fractures on CT and at autopsy are both based on subjective assessments depending on the experience of the examiner. The detectability of tiny fractures on CT additionally depends on the image quality. Although in postmortem radiology CT protocols can be adjusted and the radiation dose altered to increase image quality compared to clinical radiology [46], CT is still limited by its technical conditions, e.g. the minimal slice thickness. The application of a μCT on removed tissue may overcome these limitations and depict even the tiniest of fractures [14, 15]. However, access to μCT scanners is currently limited. Additionally, this method requires en-bloc-resections; thus, visual and manual assessments of the hyoid bone and the superior horns of the thyroid cartilage are not possible at autopsy.

In some cases, it can be difficult to assign a fracture to either the circumstances of death or to the extensive dissection of the laryngeal structures during autopsy [45]. Postmortem CT allows for an in situ depiction of findings prior to autopsy that may allow ruling out iatrogenic injuries. Additionally, CT may reveal hidden findings related to strangulation or trauma to the neck in cases that were initially not assumed to be cases of strangulation. Hyoid or thyroid fractures may be missed or overlooked during conventional autopsies [47]. The detection of such findings prior to autopsy allows a forensic pathologist to perform an appropriate dissecting technique for the neck [20]. Schulze et al. [31] demonstrated that a small gas bubble near a traumatized lesion on postmortem CT can be associated with the presence of laryngeal fractures. Thus, postmortem CT can serve as a triage tool for autopsy concerning hyoid and thyroid fractures.

The detection of hemorrhages in strangulation cases can be described as a "vital sign" [3, 48], meaning that this finding proves that the deceased was still alive until the incident. Postmortem MRI demonstrated almost equal results to those at autopsy regarding the detection of hemorrhages. In general, MRI is appropriate for the detection of hemorrhages because of iron compounds in the blood [49]. Yen et al. [25] considered the detection of a lymph node hemorrhage as a possible indicator of manual strangulation. Although subcutaneous hemorrhages were detected by CT and MRI, only MRI was able to indicate lymph node hemorrhages in all four cases of manual strangulation and in only one of five cases of hanging.

Apart from the detection of hemorrhages, special MRI techniques may provide further information regarding the extent and mechanism of neck injuries in strangulation cases. For example, Haakma et al. [50] described high-resolution depictions of the cervical spine and its nerve roots in decedents using diffusion tensor imaging (DTI), which may be supportive in the assessment of injuries to the head and neck.

The application of contrast agents may improve the detection of soft tissue lesions via contrast agent leakage into hematomas [26]. Postmortem angiography may also depict carotid artery dissection or thrombosis after strangulation, as described in clinical and perimortem imaging [51, 52]. However, there are also some limitations in performing postmortem angiography prior to autopsy. Although the application of polyethylene glycol and iodine-based water-soluble radiographic contrast might have minimal effects on histological examinations [53], contrast agents still alter the hapticity of tissue and cause discoloration, which adversely affect autopsies.

In addition to hemorrhages, the depiction of gas within the soft tissue is considered a "vital sign" in strangulation. Postmortem CT and MRI allows depiction of gas accumulations in the soft tissue. This "vital sign" was present in more than one-quarter of all hanging deaths. Additionally, one case report described the depiction of gas within the soft tissue on postmortem CT in pediatric hanging [21]. In fact, the detection of gas in hanging was already described using X-ray in the early 1970s [54]. In postmortem imaging, the presence of gas within the soft tissue is mostly associated with decomposition-related changes. Thus, assigning gas within the soft tissue to strangulation while neglecting the effects of decomposition can be difficult. Apart from the occurrence of a possible "cracking noise" at dissection [24], it can be difficult to detect this form of a "vital sign" during conventional autopsies [24, 48]. At autopsy, the preparation of structures in layers may rather indicate soft tissue emphysema as frothy air, soap bubble-like formations between the neck muscles and the ligature mark [55].

Several articles additionally examined the head, but only Wallace et al. [22] mentioned strangulation-related findings in the brain. On clinical CT after severe strangulation, low-density areas on CT [56, 57] and T1 and T2 hyperintensities [58] in the basal ganglia and the thalamus were described in single cases. However, alterations in the basal ganglia and the thalamus may be difficult to assess with postmortem CT or MRI due to the frequent presence of brain edemas or postmortem-related normal changes in image contrasts. Additionally, a strangulation-related intracerebral hemorrhage was described in clinical radiology [53]. Apart from Wallace et al. [22], who detected subarachnoid hemorrhages in both cases of judicial hanging, none of the authors reported any intracranial hemorrhages.

In conclusion, postmortem CT may be an appropriate method for the detection of hyoid and thyroid fractures, as well as gas within the soft tissue, but this imaging method seems less appropriate for the detection of hemorrhages. Postmortem MRI is the recommended modality for the detection of hemorrhages in strangulation. Consequently, only performance of both imaging modalities may keep pace with autopsy. In cases of suicidal strangulation, given clear circumstances and an obvious sequence of events, autopsy may be waived and CT combined with MRI may provide an adequate, alternative method to autopsy. In cases of accident or homicide, autopsy combined with histology and toxicology should be the primary examinations. With consideration of time constraints, CT (if not on-site) and MRI will play a marginal role, as the additional value of these methods is still disputed because the literature is lacking large-scale studies for relevant findings on CT and MRI related to strangulation. Further studies involving an adequate number of cases are desirable.

Key points

1. Postmortem CT demonstrated equivalent results to autopsy for the detection of hyoid and thyroid fractures but (non-enhanced) CT is not reliable for the detection of hemorrhages in the neck.
2. According to a small number of investigated cases, postmortem MRI demonstrated almost equivalent results to autopsy for the detection of hemorrhages in the neck.
3. Compared to autopsy, postmortem CT and MRI shows advantages in the detection of pneumomediastinum and soft tissue emphysema; however, assigning gas within the soft tissue to strangulation while neglecting the effects of decomposition can be difficult.
4. "Vital signs" in hanging can be detected by means of CT (gas within the soft tissue) and MRI (hemorrhages and gas within the soft tissue).
5. The current literature is lacking large-scale studies for relevant findings on CT and MRI related to strangulation.

Compliance with ethical standards

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

Ethical approval Not required for this systematic review.

Informed consent Not required for this systematic review.

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