Strengths and Weaknesses of Non-enhanced and Contrast-enhanced Cadaver Computed Tomography Scans in the Teaching of Gross Anatomy in an Integrated Curriculum

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Cadaver-specific postmortem computed tomography (PMCT) has become an integral part in anatomy teaching at several universities. Recently, the feasibility of contrast-enhanced (CE)-PMCT has been demonstrated. The purpose of this study was to identify particular strengths and weaknesses of both non-enhanced and contrast-enhanced PMCT compared to conventional cadaver dissection. First, the students’ perception of the learning effectiveness of the three different modalities have been assessed using a 34-item survey (five-point Likert scale) covering all anatomy course modules. Results were compared using the nonparametric Friedman Test. Second, the most frequent artifacts in cadaver CT scans, were systematically analyzed in 122 PMCT and 31 CE-PMCT data sets to quantify method-related limitations and characteristics. Perfusion quality was assessed in 57 vascular segments (38 arterial and 19 venous). The survey was answered by n = 257/320 (80.3%) students. Increased learning benefits of PMCT/CE-PMCT compared to cadaver dissection were found in osteology (2/3 categories, \( P < 0.001 \)), head and neck (2/5 categories, \( P < 0.01 \)), and brain anatomy (3/3 categories, \( P < 0.01 \)). Contrast-enhanced-PMCT was perceived particularly useful in learning vascular anatomy (10/10 categories, \( P < 0.01 \)). Cadaver dissection received significantly higher scores compared to PMCT and CE-PMCT in all categories of the abdomen and thorax (7/7 categories, \( P < 0.001 \)), as well as the majority of muscular anatomy (5/6 categories, \( P < 0.001 \)). Frequent postmortem artifacts (total n = 28, native-phase n = 21, contrast injection-related n = 7) were identified and assessed. The results of this work contribute to the understanding of the value of integrating cadaver-specific PMCT in anatomy teaching. Anat Sci Educ 0: 1–12. © 2020 The Authors. Anatomical Sciences Education published by Wiley Periodicals LLC on behalf of American Association for Anatomy.

Key words: Gross anatomy education; medical education; radiology education; computed tomography angiography; postmortem imaging; cross-sectional anatomy

INTRODUCTION

Radiologic imaging techniques are increasingly applied in the anatomy laboratory and the utilization of cadaver-specific computed tomography (PMCT) has become an integral part in gross anatomy teaching of several universities worldwide (Chew et al., 2006; Jacobson et al., 2009; Lufler et al., 2010; Bohl et al., 2011; Murakami et al., 2014; Buenting et al., 2016; Paech et al.,...
In 2011, 78% of European medical schools reported to use radiological imaging data in undergraduate anatomy teaching (Kourdioukova et al., 2011). Recently, the feasibility of using contrast-enhanced (CE-) PMCT in the framework of a gross anatomy curriculum has additionally been demonstrated (Riederer et al., 2016; Paech et al., 2018). Both, non-enhanced and CE-PMCT play an increasing role additionally to the conventional cadaver dissection course (CCD) in anatomy laboratories (Lufer et al., 2010; Bohl et al., 2011; Phillips et al., 2013; Slon et al., 2014; Paech et al., 2018; Binder et al., 2021). Several studies showed significant learning benefits of PMCT, particularly in head and neck anatomy (Lufer et al., 2010; Paech et al., 2017). Moreover, cadaver-specific PMCT has been shown to improve students’ understanding of the spatial arrangement of anatomical structures and their sometimes complex neighborhood relationships (Slon et al., 2014; Colucci et al., 2015; Dappa et al., 2016; Eid et al., 2017; Paech et al., 2017). The close interlinking of manual dissection and cadaver-specific radiology imaging in the undergraduate medical curriculum is a realistic and practice-orien tated approach to promote early clinical skills of medical students. Even though there is general agreement that these novel learning modalities increase students’ motivation and learning outcomes, quantitative assessments of modality-specific strengths and weaknesses are still missing.

To address this gap in knowledge, the purpose of this study was to investigate the modality-specific strengths and weaknesses of non-enhanced and CE-PMCT compared to conventional cadaver dissection (CCD) in an integrated curriculum comprising all teaching modalities. Therefore, n = 320 first-year medical students, who followed the universities gross anatomy curriculum (2018–2019), were invited to answer a 34-item survey in order to evaluate the three different teaching modalities. Furthermore, frequent characteristics and artifacts in non-enhanced and contrast-enhanced cadaver CT scans were systematically analyzed in 122 PMCT and 31 CE-PMCT data sets.

MATERIALS AND METHODS

This study received institutional review board (IRB) approval (S-203/2020) and was carried out between September 2018 and February 2019. All data presented in this manuscript were acquired in the course of quality assurance/quality improvement (QA/QI) measures at the Institute of Anatomy and Cell Biology at the University of Heidelberg.

Medical Curriculum at Heidelberg University

In 2013, the anatomical curriculum at the University of Heidelberg has been extended by cadaver-specific PMCT and virtual dissection modules while maintaining physical dissection as central teaching element. In 2016/17, contrast-enhanced (CE)-PMCT has been additionally established in the framework of the medical curriculum (Paech et al., 2018). The leading idea of this interactive approach was to improve the learning environment of physical dissection by adding additional learning modalities, and to link two-dimensional cross-sectional radiologic visualizations techniques with three-dimensional anatomical knowledge (Fig. 1). All students were provided with continuous access to cadaver-specific PMCT data on workstations installed next to the dissection tables. The anatomy laboratory has been equipped with 21 Intel i7-4770 3.4–3.9 GHz computers, one workstation per dissection table, each with a 27” Samsung flat screen (resolution 1920 × 1080 pixels). AnatomyMap, an image post-processing software installed on the workstations (AnatomyMap is in-house developed image post-processing software by Dr.-Ing. R. Unterhinninghofen, Institute of Anthropomatics, Karlsruhe Institute of Technology, Karlsruhe, Germany) has been designed for classroom work with an emphasis on user-friendly operation and powerful three-dimensional (3D) rendering capabilities. The AnatomyMap software allowed students to navigate by themselves through the data sets (Paech et al., 2017). It also included the possibility to link the position of the two-dimensional (2D) CT-plane in reference to the 3D renderings.

The anatomical laboratory is accompanied by tutor-guided virtual anatomy seminars and radiologic teaching sessions at life-size virtual dissection tables (Anatomage Table; Anatomage Inc., San Jose, CA). The Anatomage Table offers preinstalled CT data sets of normal anatomy and a continuously expanding collection of cases covering a variety of different diseases (anonymized patient data). Additionally, MRI scans of the head, a high-resolution atlas of regional CT anatomy, and whole body cross-sections of fresh frozen cadaver specimens are provided. These data sets could be explored as 3D reconstructions at any possible angle or be visualized as conventional cross-sections in all planes. All students had free access to the workstations and to the Anatomage Tables during daytime (available via an online reservation system).

The first-year anatomy class included in total 191.5 contact hours, with 94.5 hours allocated to lecture time, 78 hours allocated to physical dissection (with access to cadaver-specific PMCT data), and 19 hours allocated to the radiologic image interpretation seminars. For a systematic integration of cadaver-specific PMCT in gross anatomy teaching, a “virtual anatomy” manual was developed. The virtual anatomy manual guides both tutors and students by providing a module-based composition of learning targets, tasks, standardized cross-sectional planes, and a set of case studies (pathologies, variants, etc.) gathered from the repertoire of existing data sets.

These tasks were intended to stimulate interaction between both modalities. For instance, the morphology of a new dissection target can virtually been inspected prior to manual preparation, thereby allowing students to develop their personal 3D representation of anatomical structures, analogously to a surgeon who prepares an operation by studying imaging data of the patient (Paech et al., 2017).

The students have to pass oral examinations taken by docents after completion of each course module. Since 2018, these oral examinations include questions that are cadaver-related, CTRelated, or combined-modality-based (e.g., demonstration of anatomical structures first on CT data followed by a correlation in the cadaver). The newly introduced teaching elements of the anatomical curriculum have been previously reported in detail (Paech et al., 2017, 2018).

Technical Setting

Whole body cadaver CT scans were performed on an institution-owned 16-line CT scanner (Toshiba Aquilion 16; Toshiba Medical Systems Manufacturing Asia Sdn. Bhd, Penang, Malaysia) from January 2013 to December 2018 using the previously reported standardized protocol (Paech et al., 2018): head/neck (120 kV, 170 mAs, 0.5 mm slice thickness, increment 0.1 mm, kernel sharp, window brain) and thorax/abdomen/lower limb (135 kV, 75 mAs, 1.0 mm slice thickness, increment 0.5 mm, kernel sharp, window abdomen). For CE-PMCT,
the applied contrast agent Angiofil® (Fumedica AG, Muri, Switzerland) consisted of iodized linseed oil and has been developed especially for postmortem usage (Grabherr et al., 2011); 220 ml of contrast media were diluted with 3.5 L of paraffin oil. The contrast agent was injected into the femoral artery and subsequently into the femoral vein using a pneumatically driven pump (DRV1; Hellwig Individuelle Systemlösungen (HeInSys), Dautphetal, Germany), (1200 ml + 1800 ml = 3000 ml). Three CT scans have been acquired per body donor prior to the embalming procedure: The first acquisition was carried out before contrast agent administration (“non-enhanced”), the second scan was performed after intra-arterial contrast agent injection (“arterial phase”), and the third acquisition after additional intravenous injection (“arterial-venous phase”) (Fig. 1). The approach has been shown to enable good vascular filling, especially of the arterial system, including precerebral and intracerebral arteries (Paech et al., 2018). Besides contrast-enhancement of the vascular system, also the attenuation of different tissues markedly improves at CE-PMCT.

Modality Strength Survey

After completion of the first-year anatomy course in February 2019, all first-year medical students at Heidelberg University (n = 320) were invited to answer an anonymous 34-item survey, in order to evaluate the three different teaching modalities of the anatomical curriculum: (1) conventional cadaver dissection (CCD), (2) non-enhanced PMCT, and (3) CE-PMCT. The survey covered all anatomy course modules on a region- and system-based categorization (osteology, muscular system, abdomen and thorax, head and neck) with a five-point Likert scale (1 = not at all useful, 2 = slightly useful, 3 = moderately useful, 4 = very useful, and 5 = extremely useful). Furthermore, ten questions on vascular anatomy (all regions and systems) have been included. Survey reliability and internal consistency were tested using Cronbach’s alpha. The acquired survey data were ordinarily scaled and not normally distributed (Likert scale). Therefore, results were compared using the nonparametric Friedman test, followed by pairwise comparisons using the Student–Newman–Keuls (SNK) post hoc test for differences in means. Statistical analyses were performed with SigmaPlot statistical package, version 14.0 (Systat Software Inc., San Jose, CA). The level of significance was set to $P < 0.05$. Data visualizations were performed with MATLAB software, version R2020a (Mathworks Inc., Natick, MA).

Assessment of Artifacts and Frequent Pathologies in Postmortem Computed Tomography

The non-enhanced PMCT data sets from n = 122 body donors, which have been acquired between July 2013 to
October 2018, were systematically analyzed, in order to determine modality and body donor-specific characteristics/artifacts that may impede anatomy learning. Twenty-one characteristics were assessed and assigned to three possible categories (none/mild, moderate, and severe) for each body donor. These characteristics were subdivided into three different categories: (1) postmortem-related changes and/or disease, (2) age-related changes and/or disease, and (3) artifacts from metallic implants.

Assessment of Vascular Filling Defects and Contrast-Enhanced Postmortem Computed Tomography-Related Artifacts

The arterial and venous perfusion quality have been assessed in n = 31 CE-PMCT data sets (body donors of the course year 2018/19). Therefore, 38 arterial and 19 venous vessels or vascular segments were analyzed in each data set. Filling defects or wall calcifications were not evaluated according to clinical standards but with respect to suitability for teaching purposes. Accordingly, a vascular filling defect has been defined as a severe stenosis (> 70% vessel diameter) or a contrast agent discontinuation over a distance of >1 cm. Absolute and relative frequencies were calculated for all assessed items. Furthermore, the influence of the time from death to CT-scan on vascular perfusion quality was investigated. Therefore, the association between the number of regular perfused vascular segments (overall, arterial, and venous) and the time from death to CT-scan was tested over all data sets by using Spearman rank correlation.

Additionally, the most frequent postmortem artifacts due to contrast injection were assessed (seven characteristics) in all data sets. All CT data evaluations were performed in consensus by two radiologists (D.P. and K.K.) with ten and eight years of experience in postmortem CT reading.

RESULTS

Modality Strength Survey

The survey has been answered by n = 257/320 (80.3%) first-year medical students. Cronbach’s alpha test yielded a value of 0.9497. Therefore, the survey has been considered reliable with a high internal consistency. Particular strengths of CCD have been identified in muscular anatomy, such as the muscles of the forearm/hand (CCD = 4.44 ± 0.81, PMCT = 2.69 ± 1.19, CE-PMCT = 2.64 ± 1.17), the thorax anatomy. In all questions of the categories abdomen and thorax, CCD received significantly higher scores compared to PMCT or CE-PMCT (portal vein: 90.3%, splenic vein: 93.6%, and pulmonary veins 29.0%, inferior and superior vena cava, see above). The portal vein and its tributaries showed good filling (96.7%) and extracerebral head and neck venous vessels (e.g., palmar arch: 32.2% and plantar arch 22.6%). Comparably low perfusion quality was also found in thoracic organs and vascular structures (e.g., pulmonary arteries: 54.8% and heart cavities 45.2%).

Assessment of Artifacts and Frequent Pathologies in Postmortem Computed Tomography

The most common characteristics/artifacts from n = 122 PMCT data sets that may affect anatomy learning are summarized in Table 1. Regarding postmortem-related changes, collapsed large blood vessels (e.g., thoracic aorta or abdominal aorta: 9.8% moderate, 82.8% severe) and blood sediment layers in heart cavities or retroperitoneal vessels (12.9% moderate, 77.4% severe) were observed most frequently. High occurrence of postmortem artifacts in the thorax were additionally due to livor mortis in the lungs (72.95% moderate) and pleural effusions (moderate: 20.49%, severe: 31.15%). In the category of age-related changes/disease, calcifications of the choroid plexus (96.72%), arteriosclerosis (33.6% moderate, 35.3% severe), degenerative spine disease (26.2% moderate, 55.74% severe), and muscular atrophy (33.61% moderate, 35.25% severe) were most common. Figure 3 shows an example of a body donor with a prominent aneurysm of the popliteal artery found at PMCT correlated with its presentation during manual dissection. Metallic artifacts from dental implants (59.02% moderate, 6.6% severe), joint prostheses (unilateral: 14.75%, multiple: 4.92%), and osteosynthesis (26.23%) resulted in limited readability of the CT data sets in these areas.

Assessment of Vascular Filling Defects and Contrast-Enhanced Postmortem Computed Tomography-Related Artifacts

The assessment of vascular filling defects at CE-PMCT yielded over-all high perfusion quality in arterial vessels and segments (Fig. 4). Best perfusion quality was observed in the abdomen and pelvis (e.g., 100% sufficient perfusion of the splenic artery, left gastric artery, and common hepatic artery), and in the head and neck (e.g., 93.6% sufficient perfusion of the basilar artery and 80.6% of the circle of Willis). Limited arterial perfusion was observed in the distal extremities (e.g., palmar arch: 32.2% and plantar arch 22.6%). Comparably low perfusion quality was also found in thoracic organs and vascular structures (e.g., pulmonary arteries: 54.8% and heart cavities 45.2%).

Sufficient venous contrast enhancement has been found in the majority of the assessed data sets for large retroperitoneal/thoracic vessels (e.g., inferior and superior vena cava: 93.6 and 96.7%) and extracerebral head and neck venous vessels (e.g., internal and external jugular vein: 96.8 and 93.6%) (Fig. 5). In the large arteries and veins of the systemic and pulmonary circulatory systems differential fillings have been observed (aortic arch: 80.7%, pulmonary trunk: 90.3%, heart cavities: 45.2%, pulmonary veins 29.0%, inferior and superior vena cava, see above). The portal vein and its tributaries showed good filling at CE-PMCT (portal vein: 90.3%, splenic vein: 93.6%, and superior mesenteric vein: 93.6%). (In most data sets, insufficient contrast enhancement has been found in large parts of lower limbs (e.g., femoral vein: 25.8% and popliteal vein: 16.1%).

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No significant associations between the number of perfused vascular segments and time from death to CT-scan were found (overall: $r_s = -0.11, P = 0.54$; arterial: $r_s = -0.10, P = 0.59$; and venous: $r_s = -0.08, P = 0.68$). The mean time from death to CT-scan was $63.48 \pm 30.20$ hours ($2.65 \pm 1.26$ days) ranging from a minimum of 24 hours to a maximum of 120 hours.
Table 1.
Assessment of Artifacts in Non-Enhanced Postmortem Computed Tomography (PMCT) and Contrast-Enhanced Postmortem Computed Tomography (CE-PMCT)

| Characteristic                                      | None/Mild | Moderate | Severe |
|----------------------------------------------------|-----------|----------|--------|
| **Postmortem changes and/or disease**              |           |          |        |
| Collapsed thoracic aorta or abdominal aorta        | 9 (7.38)  | 12 (9.84)| 101 (82.79) |
| Blood sediment layers (retroperitoneal vessels and heart cavities) | 12 (9.68) | 16 (12.9) | 94 (77.05) |
| Livors mortis of the lungs                         | 33 (27.05)| 89 (72.95)| N/A |
| Tracheobronchial contents                          | 51 (41.8) | 29 (23.77)| 42 (34.43) |
| Autolytic gas formation in the gastrointestinal tract | 90 (73.77)| 24 (19.67)| 8 (6.56) |
| Pleural effusion (31.15% bilateral)                | 59 (48.36)| 25 (20.49)| 38 (31.15) |
| Fluid accumulation in the paranasal sinuses        | 65 (53.28)| 33 (27.05)| 24 (19.68) |
| Free abdominal liquid                              | 104 (85.25)| 17 (13.93)| 1 (0.82) |
| **Age-related changes and/or disease**             |           |          |        |
| Arteriosclerosis                                   | 38 (31.15)| 41 (33.61)| 43 (35.25) |
| Degenerative spine                                 | 22 (18.03)| 32 (26.23)| 68 (55.74) |
| Muscular atrophy                                   | 79 (64.75)| 30 (24.59)| 13 (10.66) |
| Kidney cyst(s)                                     | 89 (72.95)| 33 (27.05)| N/A |
| Gall stone(s)                                      | 111 (90.98)| 11 (9.02)| N/A |
| Aneurysm(s)                                        | 117 (95.9)| 5 (4.10) | 0 (0) |
| Calcifications of the choroid plexus                | 4 (3.28) | 118 (96.72)| N/A |
| **Artifacts from implants**                        |           |          |        |
| Metal artifacts from dental implants                | 42 (34.43)| 72 (59.02)| 8 (6.56) |
| Joint prostheses (4.92% ≥ 2)                       | 98 (80.33)| 18 (14.75)| 6 (4.92) |
| Osteosynthesis (0.82% ≥ 2)                         | 89 (72.95)| 32 (26.23)| 1 (0.82) |
| Pacemaker or defibrillator                         | 107 (87.71)| 15 (12.29)| N/A |
| Port                                               | 114 (93.44)| 8 (6.56) | N/A |
| Artificial heart valves, stents, and catheters     | 107 (87.71)| 15 (12.29)| N/A |
| **Artifacts in CE-PMCT due to contrast agent injection** | Not subclassified | |
| Extravasation of contrast agent in nasal sinuses/ oral cavity | 3 (9.70) | |
| Extravasation of contrast agent in the abdomen (pancreas, gastrointestinal tract) | 27 (87.10) | |
| Enhancement of the bowel mucosa\(^\text{a}\)       | 29 (93.60) | |
| Vascular air-trapping                              | 16 (51.60) | |
| Injection site (femoral artery/ vein): soft tissue defect and paravasation | 4 (12.90) | |
| Contrast agent filling defect due to vascular stent(s) | 1 (3.20) | |
| Deformation of vessels (expansion of collapsed vessels)\(^\text{a,b}\) | 25 (80.60) | |

Summary of postmortem computed tomography (PMCT) characteristics and artifacts that may influence anatomy most common findings are shown (occurrence > 2%). N/A, indicates not assessed learning and it applied only to characteristics where further differentiation into moderate/severe forms was not feasible. Most frequent artifacts found in CE-PMCT were related to the contrast agent (extravasation in the abdomen and enhancement of the bowel mucosa).\(^\text{a}\)The artifacts “enhancement of the bowel mucosa” and “deformation of vessels (expansion of collapsed vessels)” do not have a negative effect on the image quality, but rather increase data readability and learning perception;\(^\text{b}\)Large vessel expansion following contrast injection has been assessed for the large retroperitoneal vessels (abdominal aorta and inferior vena cava). Number of body donors assessed in non-enhanced PMCT (n = 122) and CE-PMCT (n = 31).
The most frequent postmortem artifacts due to contrast injection were contrast agent extravasation in the abdomen (gastrointestinal tract and pancreas: 87.1%) and enhancement of the bowel mucosa (93.6%) (Table 1). In 80.6% of all data sets, injection of contrast media yielded an expansion of collapsed large vessels. The bowel mucosa enhancement and expansion of collapsed vessels are two artifacts that do not have a negative effect on the image quality, but rather increase data readability. All assessed postmortem artifacts caused by contrast injection are listed in Table 1.

**DISCUSSION**

In this study, modality-specific strength and weaknesses of conventional cadaver dissection and cadaver-specific postmortem CT have been identified through a region- and anatomical system-based evaluation of the different course learning modalities by 257 first-year medical students. Furthermore, systematic assessments of postmortem CT artifacts in 122 non-enhanced and 31 contrast-enhanced whole-body CT data sets have been performed.
The haptic learning experience during dissection has highly been appreciated by medical students in the thorax and abdomen region, and throughout the muscular system. Postmortem computed tomography and CE-PMCT have been evaluated particularly helpful in head and neck anatomy and the vascular system, where the 3D rendering techniques aid to understand spatial arrangements and complex anatomical regions. In the following, the modality-specific strength and weaknesses are discussed for the different anatomical regions and systems, separately.

### Osteology

The X-ray opaque representation of bony structures makes teaching osteology with high-resolution PMCT data sets very successful. Accordingly, students gave higher ratings in these categories. Moreover, pathological findings (e.g., fractures or metal implants) motivate students to correlate these imaging findings with dissection, which are comparably easy to identify (O’Donnell et al., 2011; Jalalzadeh et al., 2015). Postmortem computed tomography allows students to start learning anatomy on “their individual body donor” at the very early stage of the class, which is not possible at the cadaver because it is surrounded by soft tissue. Beyond these motivational aspects, the strong 3D-rendering techniques of available image post-processing software (in this work AnatomyMap and the Anatomage Table) enable enlargement of small structures, rotations, and image reconstructions at any angle. However, cadaveric rigidity sometimes hinders adequate positioning of the extremities during postmortem CT-scanning (Nioi et al., 2019). This could be an explanation why no significant differences were found in the category “short bones.”

### Muscular System

The survey scores of the upper and lower limbs clearly pointed out that the students recognize a particular strength of CCD in this topic. The muscles of the lower parts of extremities (lower arm/ lower leg) are relatively thin and the contrast between different structures is limited. In PMCT, good visualization of individual muscles mainly depends on intramuscular fat tissue and muscle thickness, which strongly varies among body donors (Goodpaster et al., 2000; Engelke et al., 2018; Paech et al., 2018).

### Thorax

Medical students have found particular advantages of CCD over PMCT in studying thorax anatomy. This result is in line with the fact that pronounced postmortem CT artifacts...
are particularly found in the thorax (Bruguier et al., 2013; Slon et al., 2014; Filograna and Thali, 2017). Accordingly, the assessment of CE-PMCT data in this work yielded high frequency of livors mortis in the lungs, pleural effusions, and filling defects in thoracic organs and vessels. For instance, the normally air-filled tracheobronchial system is often obstructed with bronchial contents due high aspiration probably at the time of death (Zech et al., 2016). Consequently, these structures and topographies are difficult to read and understand in PMCT, which is in agreement with other reports in the literature (Bruguier et al., 2013; Slon et al., 2014; Filograna and Thali, 2017; Sutherland and O’Donnell, 2018).

Abdomen

The abdominal cavity and organs are relatively large compared to other regions of the body. Students have enough space to explore and study anatomical structures during cadaver dissection. Autolytic gas formation can cause limited data quality of some PMCT scans (Sapienza et al., 2017; Cartocci et al., 2019). This together may explain the comparably high scores of CCD for abdominal anatomy.

Head and Neck, Brain

Using non-enhanced and CE-PMCT, strong learning benefits were found in the students’ evaluation of head and neck anatomy. This result is in agreement with previous studies reporting the complex anatomy of the head and neck to particularly benefit from 3D and cross-sectional visualization techniques (Lufler et al., 2010; Paech et al., 2017, 2018). Additionally, CE-PMCT provided good perfusion quality of extra- and intracerebral arteries, which is one explanation for the good performance of the modality in head and neck anatomy (Bruguier et al., 2013; Paech et al., 2018). Cadaver dissection has been evaluated superior to both CT methods in the category of the palatine fossa. This could be explained by the fact that the depiction of small nerve structures is limited on CT images. In contrast, especially the pterygopalatine ganglion suspended by nerve roots from the maxillary nerve can be presented well during manual dissection.

Regarding brain macroscopy, the brain lobes, the deep gray matter, and the ventricular system can well be studied at PMCT and CE-PMCT. Additionally, some pathologic findings (e.g., midline shift, compression of the ventricular system, brain hematoma, etc.) are irreversibly lost to some extent after craniotomy during CCD. These pathologic findings are preserved.
Vascular System

The injection of contrast agent is essential for the visualization of the vascular system in PMCT (Bruguier et al., 2013; Paech et al., 2018). The CE-PMCT data sets allow students to trace vascular structures over long-distance (e.g., upper and lower limbs), which is only possible to a limited extent in the dissected cadaver. The seminars and tutor-guided sessions at the CT workstations and Anatomage Tables include specific tasks and demonstrations, where vascular structures are traced down from proximal to distal parts including depiction of important branches. Without contrast enhancement, this can only be realized in cross-sectional planes. The CE-PMCT allows the application of 3D-rendering techniques, which help to improve understanding and spatial orientation by reducing the information content on the structure of interest. Accordingly, students have evaluated CE-PMCT as highly suitable learning modality in all questions on vascular anatomy. This finding is supported by the analysis of arterial and venous perfusion quality in CE-PMCT. Except form distal extremities, good arterial perfusion quality was found in the majority of the assessed vascular structures. The venous perfusion and pulmonary circulation quality was comparably low. This could be explained by postmortem blood pooling in the thin-walled venous system causing filling defects in CE-PMCT. Alternatively, more contrast medium needs to be administered, in order to achieve better filling in these compartments. However, intravenous-enhanced data sets are of minor importance for teaching purposes. Generally, no significant associations between the number of perfused vascular segments and time from death to CT-scan were found for both arterial and venous perfusion quality. Consequently, there seems to be no stringent limit on the time span from death to contrast-enhanced CT-scan. This result is important for other institutions considering the implementation of CE-PMCT in the medical curriculum, since the period from death to embalming procedure can vary widely. In this context, it should also be noted that all cadavers were refrigerated in the period from death to embalming.

Studying the vascular system using CT data from the clinical department (Phillips et al., 2012; Jang et al., 2018), 3D interactive eLearning anatomic/radiologic education (Pettersson et al., 2009; Marker et al., 2010; Webb and Choi, 2014; Mathiowetz et al., 2016; Trelease, 2016), and conventional anatomy atlases are easier accessible and less resource-expensive alternatives compared to CE-PMCT. However, the cadaver-specific CE-PMCT approach has the strong motivational aspect of providing students with data of “their body donors.” Moreover, this direct link between both modalities helps to create synergies during anatomy learning bidirectionally: Students can plan their dissection steps using the cadaver-specific data or, vice versa, correlate their dissection findings (anatomical structure, variants, abnormalities, etc.,) with their presentation in the CT images.

Artifacts and Age-related Changes in Non-Enhanced and Contrast-Enhanced Postmortem Computed Tomography

In this work, most common artifacts and age-related changes found in non-enhanced and CE-PMCT have been assessed. The effects of these characteristics on the suitability of PMCT as teaching modality need to be discussed in a differentiated way. On the one hand, there are artifacts, such as autolytic gas formation or sediment layers in the cardio-vascular system that complicate the interpretation and reading of CT scans. Such artifacts have a negative impact on the learning experience of medical students (see above). On the other hand, artifacts due to pathology and age-related changes (e.g., implants, gallstones, and aneurysms) increase the students’ motivation to correlate anatomical presentation during manual dissection with the corresponding visualization in the radiologic image data. Some artifacts, such as the enhancement of the bowel mucosa and the expansion of previously collapsed vessels following contrast injection, do even increase image readability. Furthermore, the inclusion of exemplary clinical cases and pathologies highlights the clinical relevance of sound anatomical knowledge (Rizzolo et al., 2006; Rengier et al., 2009; Sugand et al., 2010; Slon et al., 2014; Estai and Bunt, 2016). Consequently, these artifacts have a distinct positive effect on the motivation to learn.

Generally, it should be considered that cadaver-specific PMCT data sets vary in quality due to different body constitutions and diseases, as shown in this work. Some of these artifacts are well-known in the medico-legal medicine (Bruguier et al., 2013; Sutherland and O‘Donnell, 2018). In such situations, where conditions negatively affect anatomy learning, reference CT data sets can help to ensure equal learning conditions for all students. To further improve the quality of postmortem imaging, it would be desirable to additionally acquire postmortem MRI scans, especially for brain anatomy, since MRI data provide more detailed information about soft tissues. One previous study comparing several imaging techniques in cadavers, reported very good MRI image quality of joints (shoulder and knee) for anatomy teaching (Schramek et al., 2013). The long-term impact of radiology education in the preclinical course, both on anatomy knowledge (Erkonen et al., 1992) and students attitudes toward radiology (Branstetter et al., 2008), should further be investigated in forthcoming studies.

Limitations of the Study

This study had limitations: In this work, no quantitative data of learning performance resulting from training with the different modality have been acquired. Such studies, requiring prospective randomized-controlled trials, have been previously performed and published in the literature (Paech et al., 2017, 2018).

The number of questions used in the students’ evaluation questionnaire (n = 34) cannot cover all anatomical regions in full depths. However, the questions and topics were related to the gross anatomy curriculum and represented all course modules. Furthermore, the list of assessed postmortem changes and artifacts in PMCT and CE-PMCT included twenty–eight characteristics (Table 1), which should not be considered as complete list. The assessment included twenty-one most frequent artifacts of non-enhanced PMCT plus seven frequently seen artifacts due to contrast injection in CE-PMCT. The frequency of pathologic changes found in this study is dependent on the study sample and may vary, especially among different countries and ethnic groups. However, the relatively large study sample (n = 122+31) limits statistical variance to some extent. Finally, an implementation of CE-PMCT in the medical curriculum is relatively expensive, requiring both human and material resources, possibly limiting an immediate applicability at some universities.
CONCLUSIONS

During the last few decades, a large variety of new technologies (e.g., CT/MRI/ultrasound) and teaching approaches have been introduced in the anatomy class.

A systematic integration of cadaver-specific PMCT and CE-PMCT in the universities’ anatomy curricula would mean a paradigm-shift to the field. The results of this work may motivate and justify such initiatives, in places where the relatively time- and resource-intensive conditions can be fulfilled. The interactive and multimodal approach is highly appreciated by medical students and particularly effective, since the different learning modalities offer specific strength and weaknesses that complement each other.

The knowledge about the strength and weaknesses of this novel teaching modality paves the way to achieve the best possible implementation of postmortem CT in gross anatomy teaching. The study also showed that the 3D presentation in situ and tactile experience of cadaver dissection is highly valued by medical students, particularly in abdominal and thoracic anatomy, and cannot be fully substituted by virtual tools. Postmortem computed tomography should, therefore, be regarded as a perfect complement to cadaveric dissection, rather than a substitute.

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