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Comparison of postmortem whole-body contrast-enhanced microfocus computed tomography and high-field magnetic resonance imaging of human fetuses

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KEYWORDS: fetal anatomy; high-field magnetic resonance imaging; human fetus; microfocus computed tomography; postmortem whole-body fetal imaging

CONTRIBUTION

What are the novel findings of this work?
This is the first study to compare microfocus computed tomography (micro-CT) and high-field magnetic resonance imaging (HF-MRI) in postmortem whole-body fetal imaging. We have shown that micro-CT enables higher quality imaging, with higher resolution, image contrast and signal-to-noise ratio, compared with HF-MRI. Furthermore, the ability to recognize and assess anatomical structures is greater when using micro-CT images.

What are the clinical implications of this work?
This work represents advancement in postmortem fetal imaging as a service for parents who have experienced early pregnancy loss. Previously, it was assumed that the performance of HF-MRI and micro-CT was similar and that the choice of the imaging modality should depend on availability. Here, we provide substantial evidence that micro-CT is superior to HF-MRI and, therefore, should be the preferred imaging modality.

ABSTRACT

Objective *Although fetal autopsy is generally recommended to confirm or refute the antemortem diagnosis, parental acceptance of the procedure has fallen over time, mainly due to its invasiveness. Contrast-enhanced microfocus CT (micro-CT) and high-field magnetic resonance imaging (HF-MRI, ≥ 3 Tesla) have both been suggested as non-invasive alternatives to conventional fetal autopsy for fetuses < 20 weeks of gestation. The aim of this study was to compare these two modalities in postmortem whole-body fetal imaging.*

Methods *In this study, the imaging process and quality of micro-CT and HF-MRI were compared using both qualitative and quantitative assessments. For the qualitative evaluation, fetal anatomy experts scored 56 HF-MRI and 56 micro-CT images of four human fetuses aged 13–18 gestational weeks on two components: overall image quality and the ability to recognize and assess 21 anatomical structures. For the quantitative evaluation, participants segmented manually three organs with increasing complexity to assess interobserver variability. In addition, the signal-to-noise and contrast-to-noise ratios of five major organs were determined.*

Results *Both imaging techniques were able to reach submillimeter voxel size. The highest resolution of micro-CT was 22 μm (isotropic), while the highest resolution of HF-MRI was 137 μm (isotropic). The qualitative image assessment form was sent to 45 fetal anatomy experts, of whom 36 (80%) responded. It was observed that micro-CT scored higher on all components of the qualitative assessment compared with HF-MRI. In addition, the quantitative assessment showed that*

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micro-CT had lower interobserver variability and higher signal-to-noise and contrast-to-noise ratios.

Conclusions *Our findings show that micro-CT outperforms HF-MRI in postmortem whole-body fetal imaging in terms of both quantitative and qualitative outcomes. Combined, these findings suggest that the ability to extract diagnostic information is greater when assessing micro-CT compared with HF-MRI images. We, therefore, believe that micro-CT is the preferred imaging modality as an alternative to conventional fetal autopsy for early gestation and is an indispensable tool in postmortem imaging services.* © *2021 The Authors. Ultrasound in Obstetrics & Gynecology published by John Wiley & Sons Ltd on behalf of International Society of Ultrasound in Obstetrics and Gynecology.*

INTRODUCTION

Following stillbirth, termination of pregnancy for congenital anomaly or intrauterine fetal demise, it is often recommended to perform fetal autopsy to confirm or refute the antemortem diagnosis. Fetal autopsy can provide additional diagnostic information in 40–70% of cases, which can help establish the cause of death and provide answers for bereaved parents[1]. Furthermore, these findings can be relevant for the management of future pregnancies[1,2].

However, parental acceptance of fetal autopsy has decreased over time, mainly due to the invasiveness of the procedure[3,4]. In recent years, non-invasive alternatives have been suggested, including postmortem magnetic resonance imaging (MRI)[5–7], radiography and computed tomography (CT)[8,9]. These alternatives are preferred increasingly by parents, since they do not harm the integrity of the body[4].

Despite this preference, most imaging techniques are suitable only for fetuses > 20 weeks of gestation due to low resolution and/or poor soft-tissue contrast[10–14]. In addition, early gestational loss (< 20 weeks) requires specialist high-resolution imaging due to small fetal size. Imaging modalities such as high-field MRI (HF-MRI, ≥ 3 Tesla (T)) and microfocus CT (micro-CT) are potential options for the latter group[15]. Due to increased magnetic field strength, HF-MRI allows submillimeter spatial resolutions, enabling detailed examination of fetal anatomy, including the brain[16–18], inner ear[19] and extremities[20]. Micro-CT, combined with a contrast agent (contrast-enhanced micro-CT), has also been shown to have a high concordance rate with fetal autopsy[13,21].

Although both micro-CT and HF-MRI appear feasible for postmortem fetal imaging, the choice of imaging technique is currently based mainly on the availability of imaging equipment rather than their specific advantages and disadvantages. It has been hypothesized that the two imaging techniques lead to similar results[15], but they have not been compared directly.

The aim of this study was to make a direct comparison between micro-CT and HF-MRI in postmortem whole-body fetal imaging. Our key objectives were to assess differences between the two modalities related to qualitative and quantitative outcome measures. These results should help guide clinical decision-making and future research in this field.

METHODS

Micro-CT and HF-MRI were compared for postmortem whole-body fetal imaging, with qualitative assessment using an image quality assessment form and quantitative assessment of interobserver variability and image contrast. Human fetal specimens were obtained from the Dutch fetal biobank, located at Amsterdam University Medical Centers (Amsterdam UMC), location AMC, Amsterdam, The Netherlands. The Dutch fetal biobank contains structurally and genetically normal and abnormal fetuses between 6 and 24 weeks of gestation that were donated after medically induced termination of pregnancy, ectopic pregnancy removal or very preterm delivery (< 24 weeks). Ethical approval was granted by the accredited Medical Research Ethics Committee Amsterdam UMC (METC 2016_285, #B2017369). Maternal and paternal written informed consent for donation to the Dutch Fetal Biobank was obtained after decision-making and prior to termination of pregnancy/delivery. As this study was within the scope of the biobank, no additional consent was required.

Four human fetuses aged 13–18 gestational weeks, weighing 17–137 g and with crown–rump length of 6–13 cm, were selected and imaged (Table 1). Both micro-CT and HF-MRI are used currently for research on specimens in this gestational-age range. All specimens were collected *in toto* after induced termination of pregnancy using misoprostol because of a trisomy 21 diagnosis. Following collection, the fetuses were fixed in 4% paraformaldehyde for 2–7 days at 4°C, depending

Table 1 Overview of postmortem specimens examined using microfocus computed tomography (micro-CT) and high-field magnetic resonance imaging (HF-MRI)

						Resolution (μm)	
Fetus	*GA (weeks)*	*CRL (cm)*	*Weight (g)*	*Reason for TOP*	*Imaging modality*	*Micro-CT*	*HF-MRI*
1	13 + 1	6	17	Trisomy 21	Micro-CT and HF-MRI (7 T)	22	137
2	13 + 2	7	NA	Trisomy 21	Micro-CT and HF-MRI (7 T)	40	156
3	15 + 2	11	58	Trisomy 21	Micro-CT and HF-MRI (7 T)	40	195
4	17 + 2	13	137	Trisomy 21	Micro-CT and HF-MRI (3 T)	47	333

CRL, crown–rump length; GA, gestational age; NA, not available; T, Tesla; TOP, termination of pregnancy.

on fetal size, and stored in 0.2% paraformaldehyde at 4°C until imaging.

HF-MRI

The three smaller fetuses (gestational age < 16 weeks) were scanned on a preclinical 7-T MRI scanner (MR Solutions, Guildford, UK) with a 17-cm bore diameter and a maximum gradient amplitude of 600 mT/m. A 70-mm transmit/receive rat body coil was used for signal acquisition. Due to size constraints of 7-T MRI, the largest fetus (gestational age > 16 weeks) was scanned on a clinical 3-T MRI scanner (Philips Healthcare, Amsterdam, The Netherlands), with a bore diameter of 70 cm and integrated gradient coils, producing a maximum amplitude of 45 mT/m. A 160-mm transmit/receive knee coil was used for radiofrequency excitation and signal reception. We found that three-dimensional (3D) T-1w gradient-echo imaging provided the best tradeoff between imaging time, resolution and organ recognition. Other more experimental sequences, such as susceptibility-weighted and diffusion-weighted imaging, were not added because they have poor contribution in clinical postmortem fetal imaging[22,23]. The field of view and resolution were adapted to fetal size. All detailed scan parameters for each fetus can be found in Table S1.

Contrast-enhanced micro-CT

After HF-MRI imaging, all fetuses were prepared for micro-CT scanning. To ensure soft-tissue contrast, they were stained with 3.75% weight/volume Lugol's solution for 2–7 days, depending on fetal size[13]. From this point, contrast-enhanced micro-CT is referred to as micro-CT. After staining, the specimens were washed to remove excess Lugol's solution and, subsequently, stabilized in 1.5% agarose gel to prevent movement-related artifacts during scanning.

Micro-CT scans were carried out using a GE Phoenix v|tome|x m tomographer (GE Inspection Technologies, Wunstorf, Germany). The voltage (180–210 kV) and current (180–210 µA) were adjusted to the fetal size. The images were acquired with an exposure time of 333 ms and a full scan consisted of 1500 projections. To decrease source-to-object distance, resulting in a higher spatial resolution, some fetuses were scanned in two or three steps (i.e. upper and lower part of the body scanned separately and datasets merged after scanning). Phoenix datos|x 3D CT software was used for 3D reconstruction

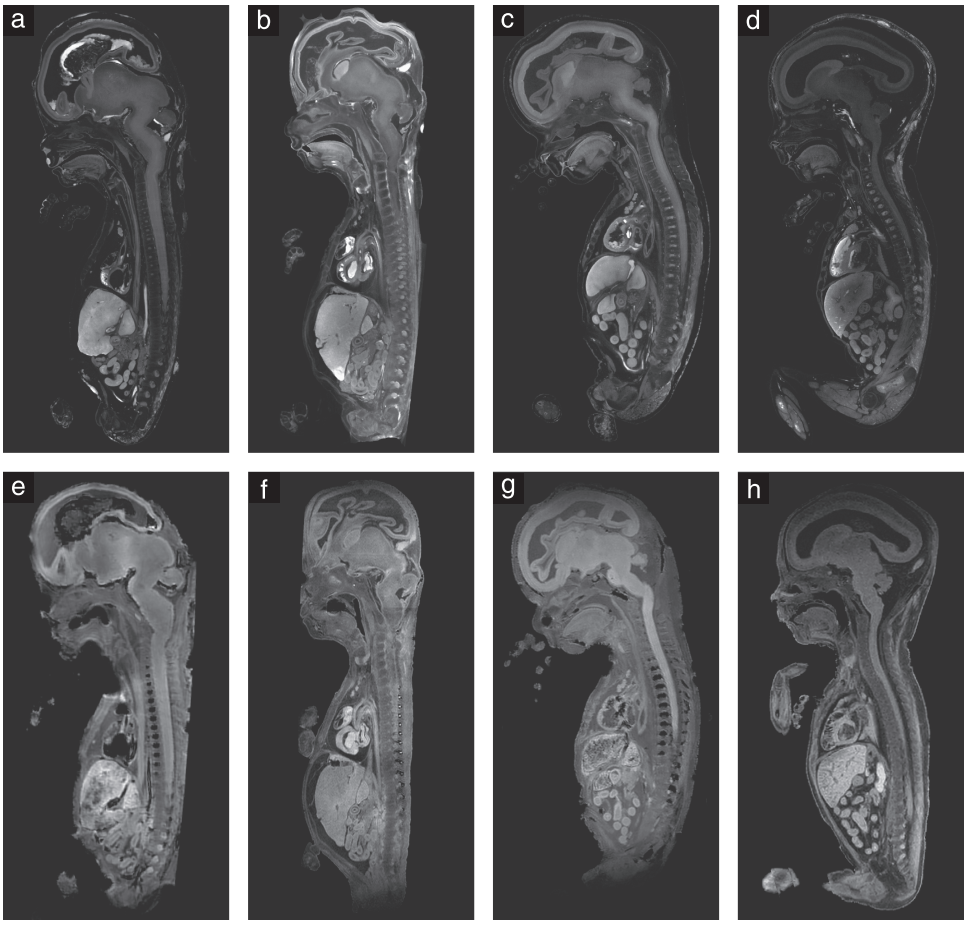


Figure 1 Representative midsagittal contrast-enhanced microfocus computed tomographic (a–d) and T1-weighted high-field magnetic resonance (e–h) postmortem images of Case 1 (a,e), Case 2 (b,f), Case 3 (c,g) and Case 4 (d,h).

of the scan data. All detailed scan parameters for each fetus can be found in Table S1.

Qualitative assessment

A total of 56 HF-MRI and 56 micro-CT images were evaluated qualitatively using an image quality assessment form, consisting of two components: overall image quality and organ recognition. All components were assessed according to a previously reported four-point quality rating scale, in which 1 is poor, 2 is moderate, 3 is good and 4 is excellent[24]. If the observers were not familiar with an anatomical structure, they were given the option to indicate that the structure is unknown (0). Castor EDC (Castor, Amsterdam, The Netherlands) was used to create and send the image quality assessment form to radiologists, perinatologists, anatomists and researchers with extensive knowledge of postmortem (fetal) imaging from different hospitals in The Netherlands and UK.

Image quality was assessed because it is the main determinant of test sensitivity and interobserver variability and influences the ability to extract diagnostic information from an image[25,26]. To score overall image quality, the observers were presented randomly with images and were asked to score them according to the four-point quality rating scale (Figure 1). Furthermore, the ability to recognize organs was assessed because reliable interpretation for research and diagnostic purposes is possible only when a structure is well-defined[26]. To assess this, 21 anatomical structures from nine organ systems were evaluated (Figure 2). The observers received multiple images, in which they scored 15 randomly selected structures from different organ systems. Micro-CT and HF-MRI images were displayed randomly. Every structure was evaluated by at least five observers.

Quantitative assessment

First, HF-MRI and micro-CT images were assessed by estimating the interobserver variability of organ volume measurements. Five experts in fetal organ segmentation were asked to outline an easy (eyeball), intermediate (stomach) and difficult (thymus) organ using Amira software (v2019.4; Thermo Scientific, Rockford, IL, USA). For every structure, five successive slices were presented in the coronal plane. To determine the extent of interobserver variability, the coefficient of variation (CV) was calculated[27].

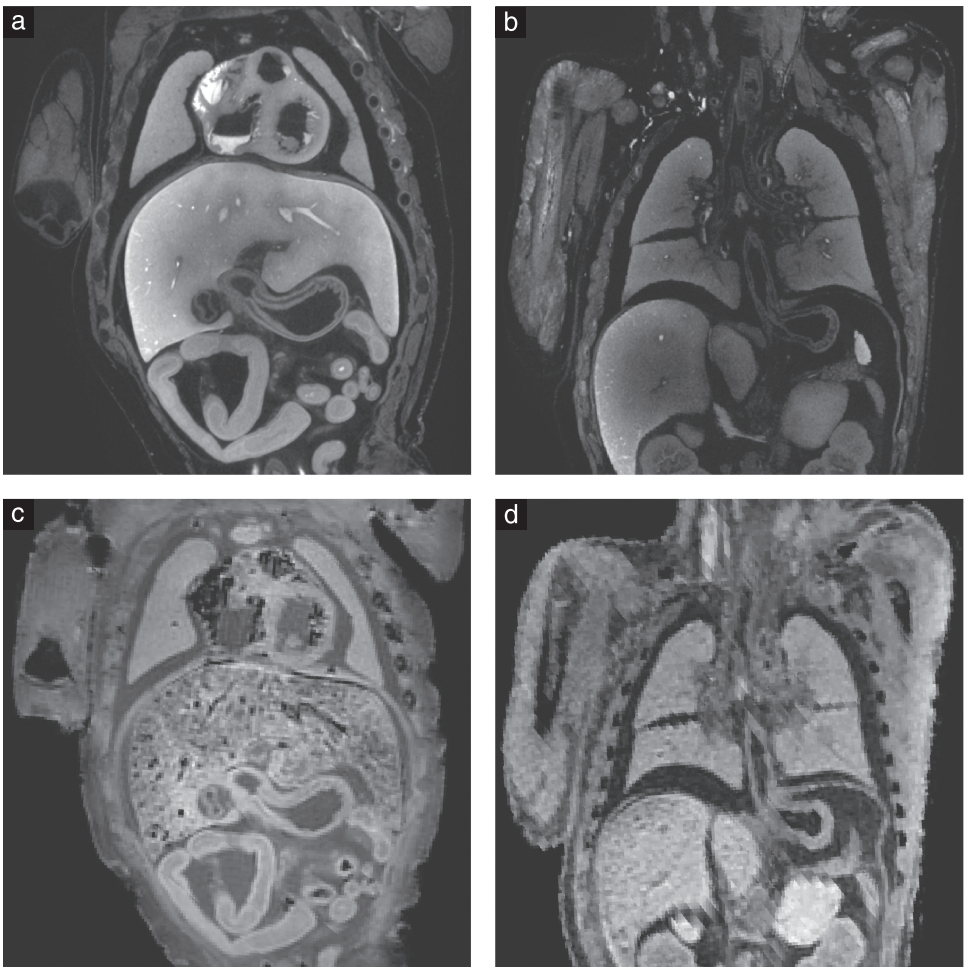


Figure 2 Organ recognition in coronal microfocus computed tomographic (a,b) and high-field magnetic resonance (c,d) images, showing liver and stomach of Case 3 (a,c) and primary bronchi and lungs of Case 4 (b,d).

Second, in HF-MRI and micro-CT images, 250 regions of interest, of 50 voxels each, were defined within and surrounding the five major organs: brain, heart, lungs, liver and kidneys. The mean signal intensity and Hounsfield units were calculated in HF-MRI and micro-CT images, respectively, using RadiAnt™ DICOM Viewer (v5.5.1; Medixant, Poznań, Poland) by one operator (C.H.). Then, the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were calculated[28].

Statistical analysis

For the qualitative evaluation, the median scores were calculated for all components of the image quality assessment form and compared using the Wilcoxon signed-rank test. For the quantitative evaluation, the mean total volumes of the eyeball, stomach and thymus were calculated from the outlines drawn by the participants and compared using a paired, two-tailed Student's *t*-test. Then, the variance of total volume measurements in HF-MRI and micro-CT images were compared using a Levene's test. Last, the mean SNR and CNR of the five major organs were calculated and compared using a paired, two-tailed Student's *t*-test. All data were analyzed using the statistical software SPSS (version 26.0 for Windows; IBM Corp., Armonk, NY, USA). A *P*-value < 0.05 was considered statistically significant.

RESULTS

Both imaging techniques were able to reach submillimeter voxel size (Table 1). In this study, the highest resolution of micro-CT was 22 µm (isotropic), while the highest resolution of HF-MRI was 137 µm (isotropic).

Image quality assessment

In total, 21 anatomical structures were assessed in 56 HF-MRI and 56 micro-CT images. To investigate the quality of these images, the image quality assessment form was sent to 45 fetal anatomy experts, of whom 36 (80%) responded. Responder and non-responder groups were similar in terms of years of experience and proportions of MRI and CT experts, hence the chance of selection bias was limited. The quality of micro-CT images was considered excellent and was significantly higher compared with HF-MRI images, which were considered to have moderate quality (median (interquartile range (IQR)) quality score, 4 (3–4) *vs* 2 (1–2); $P < 0.001$) (Figure 3). None of the micro-CT images had a lower median score than any of HF-MRI images (Table S2).

The overall ability to recognize organs was significantly higher in micro-CT compared with HF-MRI images (median (IQR) score, 3 (3–4) *vs* 2 (1–2); $P < 0.001$) (Table 2). Furthermore, in micro-CT compared with HF-MRI images, the observers had a significantly greater ability to recognize individual organs in the sensory, nervous, respiratory, immune, digestive, cardiovascular, urinary, endocrine and skeletal systems (Table 2). The observed differences were present across gestational ages and with different field strength (3T or 7T) (Table S3).

Interobserver variability

All structures examined (eyeball, stomach and thymus) had a significantly higher volume on HF-MRI compared with micro-CT images ($P < 0.001$). Interobserver variability, reflected by CV, increased when assessing more complex structures (stomach and thymus) compared with an easy structure (eyeball). Moreover, independent of the complexity of the organ, CV was higher in HF-MRI compared with micro-CT images (Figure 4, Table S4). In agreement with CV, all examined structures had a significantly greater variance of volume measurements on HF-MRI ($P < 0.001$). Both CV and variance showed that the interobserver variability in organ volume measurements was higher on HF-MRI (Figure 4).

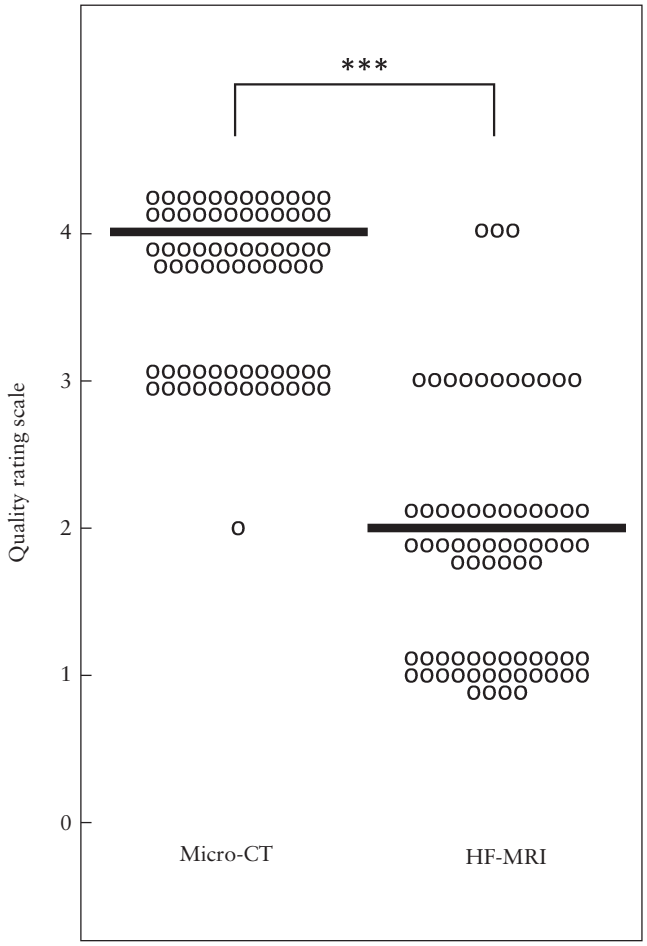


Figure 3 Subjective evaluation of overall quality of eight micro-focus computed tomographic (micro-CT) and eight high-field magnetic resonance (HF-MRI) images by 36 observers using a four-point quality rating scale, in which 1 is poor, 2 is moderate, 3 is good and 4 is excellent. Each circle represents a score by an observer and thick lines represent median scores. ***Wilcoxon signed-rank test showed a significantly higher score for micro-CT compared with HF-MRI images (median (interquartile range) score, 4 (3–4) *vs* 2 (1–2); $P < 0.001$).

Table 2 Organ recognition in microfocus computed tomography (micro-CT) and high-field magnetic resonance imaging (HF-MRI), rated by observers using a four-point quality rating scale

Structure	*Micro-CT*	*HF-MRI*	P
Overall	3 (3–4)	2 (1–2)	< 0.001
Sensory system			
Eyeball	4 (3–4)	2 (2–3)	< 0.001
Nervous system			
Cerebrum	3 (3–4)	2 (2–2)	< 0.001
Cerebellum	3 (3–4)	2 (1–2)	< 0.001
Pons	3 (3–4)	2 (2–3)	0.002
Spinal cord	3 (3–4)	2 (1–3)	< 0.001
Respiratory system			
Primary bronchi	3 (3–4)	1 (1–2)	< 0.001
Lungs	4 (3–4)	2 (2–3)	< 0.001
Immune and lymphatic system			
Thymus	3 (3–4)	1 (1–2)	< 0.001
Digestive system			
Liver	4 (3–4)	2 (1–2)	< 0.001
Stomach	4 (3–4)	1 (1–3)	< 0.001
Intestines	3 (3–4)	2 (1–3)	< 0.001
Tongue	4 (3–4)	2 (1–2)	< 0.001
Cardiovascular system			
Right atrium	3 (3–4)	1 (1–2)	< 0.001
Left atrium	3 (3–4)	1 (1–1)	< 0.001
Right ventricle	4 (3–4)	1 (1–2)	< 0.001
Left ventricle	4 (3–4)	1 (1–2)	< 0.001
Ventricular septum	4 (3–4)	2 (1–2)	< 0.001
Urinary system			
Kidneys	4 (3–4)	2 (2–3)	< 0.001
Endocrine system			
Adrenal glands	3 (3–4)	2 (1–3)	< 0.001
Skeletal system			
Vertebrae	4 (3–4)	2 (1–2)	< 0.001
Humerus	3 (2–3)	1 (1–2)	< 0.001

Data are given as median (interquartile range). Observers rated organ recognition according to four-point quality rating scale, in which 1 is poor, 2 is moderate, 3 is good and 4 is excellent.

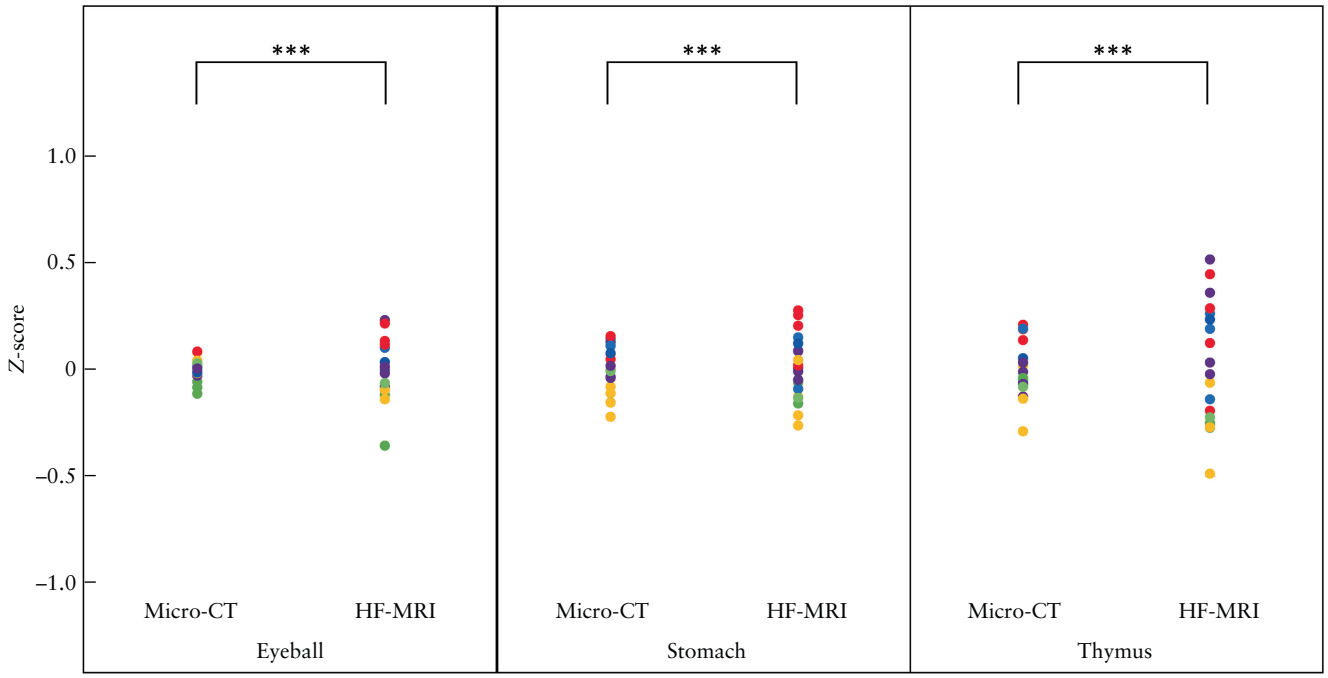
SNR and CNR

The mean SNR and CNR of all major organs were higher in micro-CT compared with HF-MRI images (Table 3). The mean SNR was 1.4–3.3-times higher in micro-CT compared with HF-MRI images, with a statistically significant difference in the SNR of the brain ($P = 0.046$), heart ($P = 0.003$), liver ($P = 0.005$) and kidneys ($P = 0.002$). Similarly, the mean CNR was 1.5–3.2-times higher in micro-CT compared with HF-MRI images, with a statistically significant difference in the CNR of the heart ($P = 0.013$), liver ($P = 0.019$) and kidneys ($P = 0.024$) (Table 3). The difference in mean SNR and CNR was comparable for all four fetuses and all organs (Table S5).

Table 3 Mean signal-to-noise (SNR) and contrast-to-noise (CNR) ratios of microfocus computed tomographic (micro-CT) and high-field magnetic resonance (HF-MRI) images for five major organs in four fetuses

	SNR			*CNR*		
Organ	*Micro-CT*	*HF-MRI*	P	*Micro-CT*	*HF-MRI*	P
Brain	64 ± 10	36 ± 10	0.046	20 ± 7	10 ± 3	0.071
Heart	47 ± 9	17 ± 4	0.003	17 ± 5	7 ± 3	0.013
Lungs	55 ± 17	39 ± 9	0.240	20 ± 5	13 ± 2	0.071
Liver	64 ± 12	22 ± 9	0.005	24 ± 8	9 ± 3	0.019
Kidneys	53 ± 9	16 ± 4	0.002	16 ± 5	5 ± 1	0.024

Data are given as mean ± SD. Comparisons were made using paired, two-tailed Student's *t*-test.



CV	1.37%	4.13%	3.79%	5.89%	6.90%	14.63%

Figure 4 Interobserver variability in segmentation and volume measurement of three organs of varying complexity by five participants (●, 1; ●, 2; ●, 3; ●, 4; and ●, 5) on microfocus computed tomographic (micro-CT) and high-field magnetic resonance (HF-MRI) images. Dots represent individual measurements by each participant, expressed as *Z*-scores. ***Variance was significantly higher in HF-MRI compared with micro-CT images (Levene's test, $P < 0.001$). The coefficient of variation (CV) was higher for HF-MRI compared with micro-CT and increased with anatomical structure complexity.

DISCUSSION

This is the first study to compare contrast-enhanced micro-CT and HF-MRI in postmortem whole-body fetal imaging. Our findings show clearly that micro-CT enables higher-quality imaging as compared with HF-MRI. Furthermore, the ability to recognize and assess organs and structures is greater when using micro-CT images. This is likely to be the result of higher resolution, image contrast and SNR of micro-CT images. These features result in increased sharpness of boundaries of anatomical structures on CT-MRI, allowing for more accurate volume measurements, and explain the lower interobserver variability of micro-CT images. This is of importance, as it is sometimes necessary to measure accurately the volume of an organ for research and diagnostic purposes[29]. Our combined findings suggest that the ability to extract diagnostic information is greater when using micro-CT compared with HF-MRI images.

No direct comparison between micro-CT and HF-MRI has been made previously, but prior studies have already theorized that micro-CT may allow acquisition of high-resolution images in a shorter scan time[13]. Although we did not use a completely standardized MRI protocol when assessing different fetuses, the average scan time was 3-times longer for HF-MRI (Table S1) and resolution 5.5-times lower. Increasing spatial resolution of HF-MRI is possible; however, reduction of voxel dimensions by a factor of two requires an increase in scan time by a factor of eight, while at the same time lowering drastically the SNR. It is, therefore, clear that HF-MRI would never achieve similar quality to that of micro-CT. The inherently long scan time also means higher costs associated with MRI (on average, around €400 per specimen) compared with micro-CT (on average, around €200 per specimen). Combining qualitative and quantitative outcomes with the higher achievable resolution in a shorter scan time shows that micro-CT is more suitable and less expensive compared with HF-MRI for postmortem whole-body fetal imaging.

This work represents further advancement in postmortem fetal imaging as a service for parents who have experienced early pregnancy loss. A stepwise diagnostic approach to fetal postmortem examination has been suggested, in which postmortem imaging could serve as a form of triage for further invasive autopsy in future guidelines[30] and HF-MRI and micro-CT were suggested to be equal, with the choice of technique depending on the locally available resources. Previously, it was assumed that micro-CT is a more practical solution for a postmortem fetal imaging center, given the high cost of MRI machinery[21]. Here, we provide substantial evidence that micro-CT is superior to HF-MRI in terms of image quality and resolution.

Clinical applicability

We believe that centers wishing to provide comprehensive postmortem imaging services for early gestation (12–20 weeks) should pursue acquisition of micro-CT equipment. From our own and others' experience, micro-CT can be operated and staining can be handled by professionals from different technical and medical backgrounds after a short period of dedicated supervised training[21,31]. However, users should bear in mind that staining of the fetus is necessary, which could hamper the clinical application of micro-CT imaging because fixation and staining could interfere with future molecular analysis, such as transcriptomics, proteomics or metabolomics, which could be an untapped diagnostic source. Nonetheless, the diagnostic tools that are available currently and used in the search for causal mutations (i.e. microarray[32] and whole-exome sequencing[33–35]) require only DNA isolated from tissue (e.g. umbilical cord or muscle–skin biopsy), which can be acquired easily prior to fixation and staining. Furthermore, several groups have shown that histological tissue analysis is not hampered by Lugol's staining[21,36]. Another limitation of micro-CT is that the necessary preparation time means longer clinical turnaround time. This could have a negative influence on the uptake, especially in Jewish and Muslim religious communities, in which it is important to bury the body as soon as possible[37]. However, this group would likely also decline conventional autopsy because of the need for incisions and would see only non-invasive alternatives as permissible, with the relatively long time until burial as a point of discussion within the community[37]. Finally, staining with Lugol's solution causes tissue shrinkage, as we have also seen in this study, in which all structures examined (eyeball, stomach and thymus) had a significantly lower volume on micro-CT images (made after staining) compared with the HF-MRI images (prior to staining)[38,39]. Recently, a new Lugol's staining protocol using a buffered Lugol's solution (B-Lugol) has been published, showing reduced shrinkage artifacts[40].

Strengths and limitations

A major strength of this study was the direct comparison of micro-CT and HF-MRI. To assess the difference in image quality, observers were provided with identical images of the same fetus scanned using both modalities. This enabled us to compare the quality of HF-MRI and micro-CT images without the confounding associated with comparing images of different fetuses. Furthermore, observers were fetal anatomy experts with years of experience in assessing and analyzing (fetal) micro-CT and HF-MRI images. Their combined experience resulted in qualitative analysis being a robust reflection of clinical practice. Moreover, the images were not scored only on qualitative outcome but also quantitative outcome measures, demonstrating that micro-CT images are not only perceived subjectively as being of higher quality, but are also superior objectively.

The relatively small number of scanned fetuses ($n = 4$) can be considered a limitation. However, in this preclinical experimental setting, the actual sample size

was considerably higher, since we compared 112 images and assessed 21 anatomical structures. Also, given the clear significant differences in image quality between the two modalities studied and the fact that HF-MRI[41] and micro-CT[42] have the same factors affecting their image quality (i.e. body weight and maceration), scanning more individual fetuses in the same age category would not have a significant impact on the results.

As we included only specimens within the age range in which both micro-CT and HF-MRI are currently studied (13–18 weeks), the findings are not generalizable to other gestational ages. However, we expect that results for fetuses < 12 weeks would be similar or even more favorable towards micro-CT, as previous research showed that micro-CT can provide excellent, histology-like images for first-trimester fetuses[43,44], not seen when using HF-MRI for fetal imaging. Another potential limitation is that the four-point quality rating scale, which has been used previously to compare quality of different images[24,45], has not been validated officially.

Conclusions

With our data, we have shown that micro-CT is superior to HF-MRI when used for postmortem whole-body fetal imaging for almost all qualitative and quantitative outcome measures assessed. Our findings suggest that the ability to extract diagnostic information is greater when using micro-CT compared with HF-MRI images. We, therefore, believe that micro-CT is the preferred imaging modality as an alternative to conventional fetal autopsy for early gestation and is an indispensable tool in postmortem imaging services.

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SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:

Table S1 High-field magnetic resonance imaging (HF-MRI) and microfocus computed tomography (micro-CT) parameters per fetus

Tables S2–S5 Subjective evaluation of overall image quality (Table S2), organ recognition (Table S3), variance in organ segmentation (Table S4) and signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) (Table S5) in microfocus computed tomography (micro-CT) and high-field magnetic resonance imaging (HF-MRI)