Deep Learning–Based Compressed Sensing Reconstruction for High-Resolution MRI of Human Embryos

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Introduction: Magnetic resonance microscopy (MRM) enables non-invasive visualization of tissue microstructures and is widely used for morphological analysis of fixed human embryo specimens [1]. However, high spatial resolution imaging typically requires prolonged acquisition times. In 2023, MRM with an isotropic resolution of (10 μm)³ was achieved [2] using compressed sensing (CS) [3] with an acceleration factor of 2 (AF=2), although the scan still required approximately 12 days. Recently, deep learning (DL)–based reconstruction methods have shown superior performance over conventional CS. Among these, zero-shot self-supervised learning (ZS-SSL) [4], which requires no external training data, is particularly promising for human embryo imaging, where the availability of annotated datasets is limited. This study aims to further accelerate high-resolution MRM of human embryos by applying ZS-SSL while preserving spatial resolution.

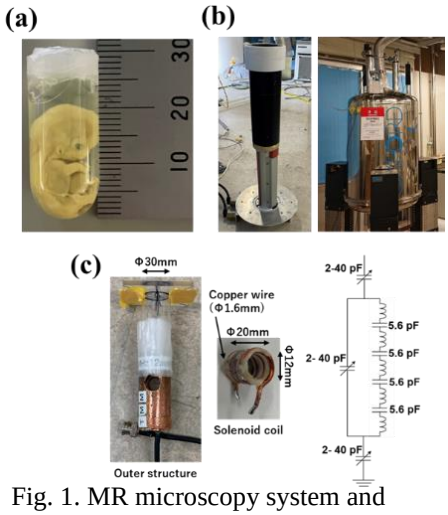

Fig. 1. MR microscopy system and embryo specimen.(a) Human embryo specimen at Carnegie stage 21 embedded in agarose gel.(b) Gradient coil and 9.4 T vertical superconducting magnet.(c) home-made RF coil and resonance circuit.

Methods: A human embryo at Carnegie stage 21 (Fig. 1(a)) was embedded in 1% agarose gel within a 12 mm-diameter test tube. Imaging was performed using a Bruker micro2.5 gradient system and a 9.4 T vertical superconducting magnet (Fig. 1(b)). A home-made RF coil was used (Fig. 1(c)). Imaging was conducted using a steady-state free precession free induction decay (SSFP-FID)–based three-dimensional gradient echo sequence with the following parameters: TR/TE=100/5 ms, flip angle=70°, FOV=1.9×1.28×1.28 cm³, and matrix size=1000×640×640, yielding an isotropic resolution of (20 μm)³. The number of excitations (NEX) was set to 24, and the total scan time was approximately 68 hours. ZS-SSL was re-implemented in PyTorch based on the method proposed by Yaman et al., using a MoDL-based architecture with a 5-layer ResNet. The learning rate was set to 5×10^{-4}, and early stopping was applied if the validation loss did not improve for 20 consecutive epochs.

Results and discussion: The reconstructed image of the accessory nerve (~100 μm in diameter) is shown in Fig. 2(b). For reference, Fig. 2(a) shows the corresponding structure in a histological section from a different embryo specimen at the same developmental stage. In the ZS-SSL reconstructed image, the accessory nerve was clearly visualized and could be distinguished from the surrounding tissue.

Conclusion: These results demonstrate that high-resolution imaging at AF=4 is feasible using ZS-SSL, achieving a fourfold acceleration without significant degradation of image quality. ZS-SSL is thus a practical and effective method for fast, high-resolution imaging of human embryos.

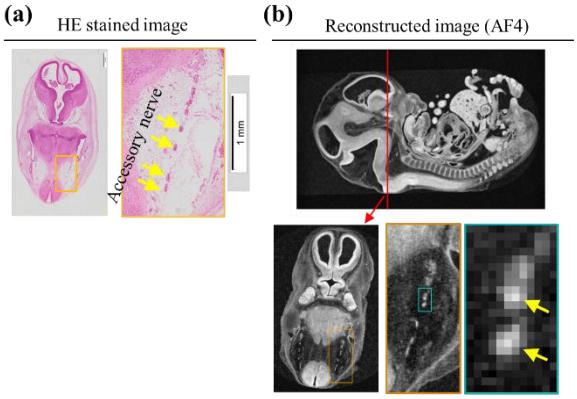

Fig. 2. Magnified images of the accessory nerve. (a) HE-stained image of a human embryo at Carnegie stage 21, used for comparison. (b) ZS-SSL reconstructed image at AF=4, showing clear visualization of the accessory nerve.

References: [1] K. Kose, Anat. Rec., 301, (2018).
[2] K. Makihara et al., J. Magn. Reson., 355, (2023).
[3] M. Lustig et al., Magn. Reson. Med., 58, (2007). [4] B. Yaman et al., Proc. ICLR, (2022).