SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Theory of Nyquist ghosts in single-shot SPEN

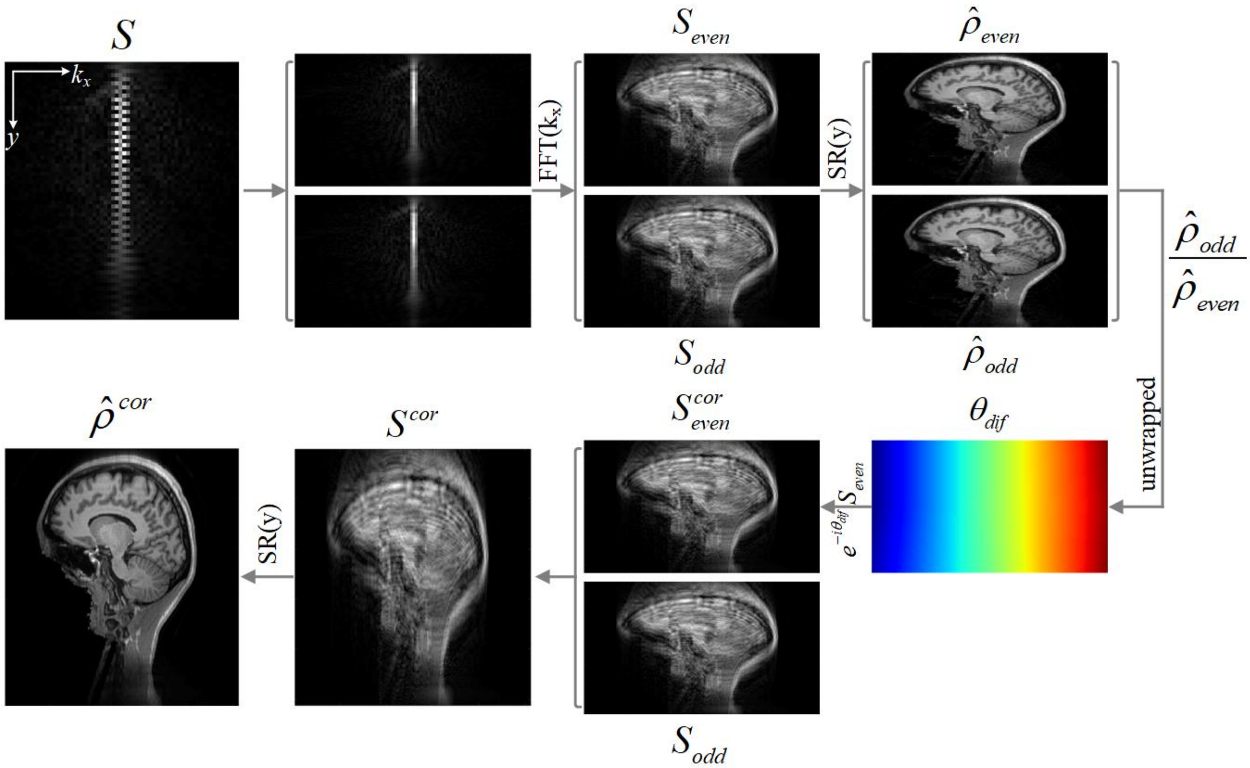


Figure S1. Details of the conventional Nyquist-ghost correction method of single-shot SPEN. Firstly, separate the even and odd rows of the original phase-distorted SPEN data, and perform FT along the RO direction to obtain low-resolution odd echo image S_{odd} and even echo image S_{even}. Secondly, perform SR reconstruction along the PE dimension to obtain high-resolution odd echo image $\hat{\rho}_{odd}$ and even echo image $\hat{\rho}_{even}$. Then, perform the quadratic polynomial fitting on $\hat{\rho}_{odd}$ and $\hat{\rho}_{even}$ to unwrap the phase difference map θ_{dif}, which is used to correct the phase of S_{even} to keep consistent with the phase of S_{odd}. And then recombine the phased-corrected low-resolution even echo image S^{cor}_{even} with S_{odd}, and obtain a full low-resolution phase-corrected SPEN image S^{cor}. Finally, perform SR reconstruction along the PE dimension to obtain a high-resolution ghost-corrected SPEN image $\hat{\rho}^{cor}$.

The structure of supervised and unsupervised method

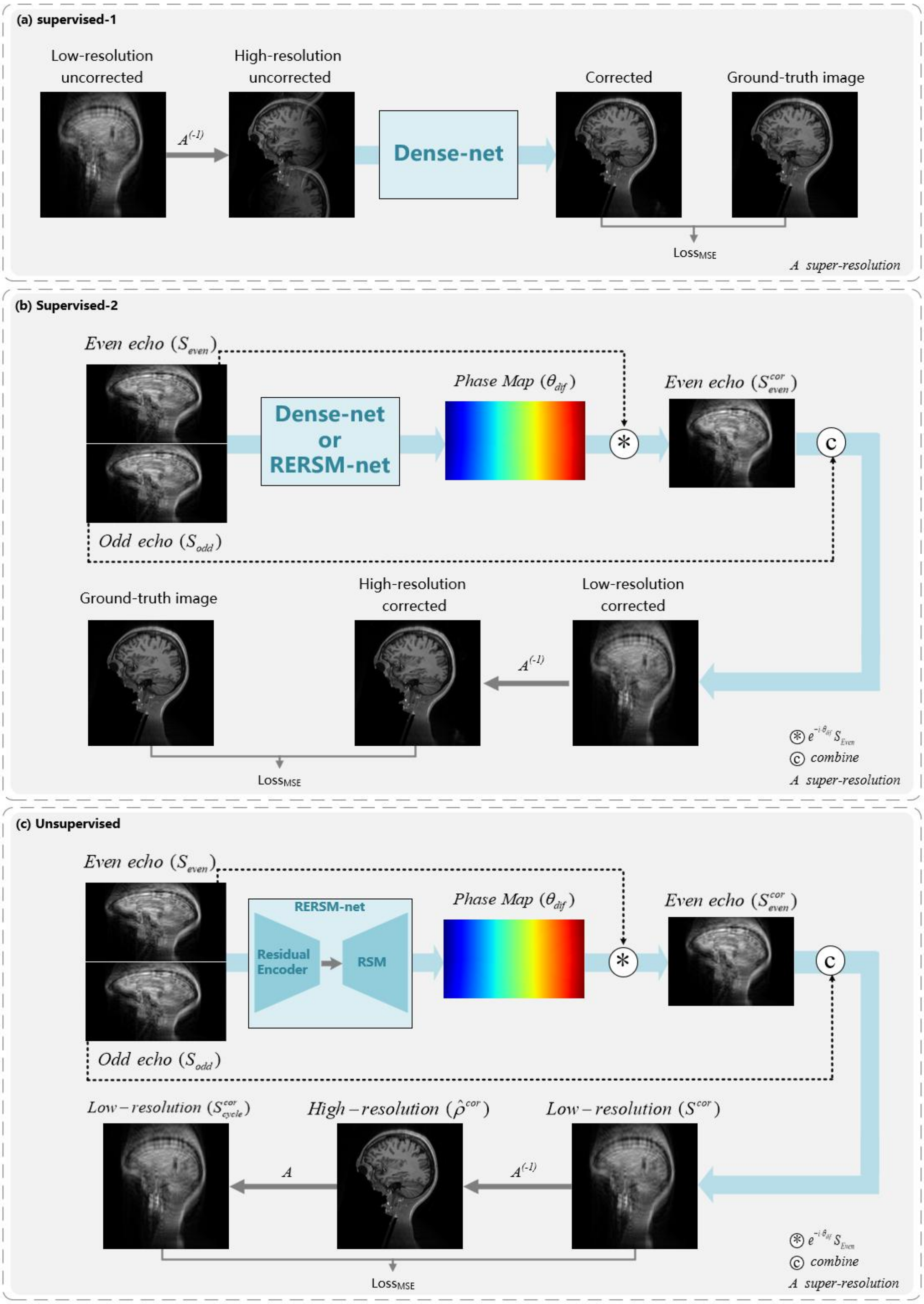


Figure. **S2** The structure of supervised and unsupervised method. (a) The supervised-1 method is to directly input the image into the network, then output the image. First, the uncorrected low-resolution image is transformed into an uncorrected high-resolution image through super-resolution, and then the uncorrected high-resolution image is sent to the Dense-net or U-net network to obtain the corrected image. Then, the loss between the corrected image and the true value image is calculated. (b) The supervised-2 method is to input the odd and even echo images into Dense-net or U-net to obtain a phase map. The phase map is used to correct the even echo image and then combined with the odd echo image to obtain a corrected low-resolution image. Finally, the corrected high-resolution image is obtained through super-resolution, and the loss is calculated using this image and the true value image. (c) The proposed unsupervised method

Production procedure of simulated SPEN data

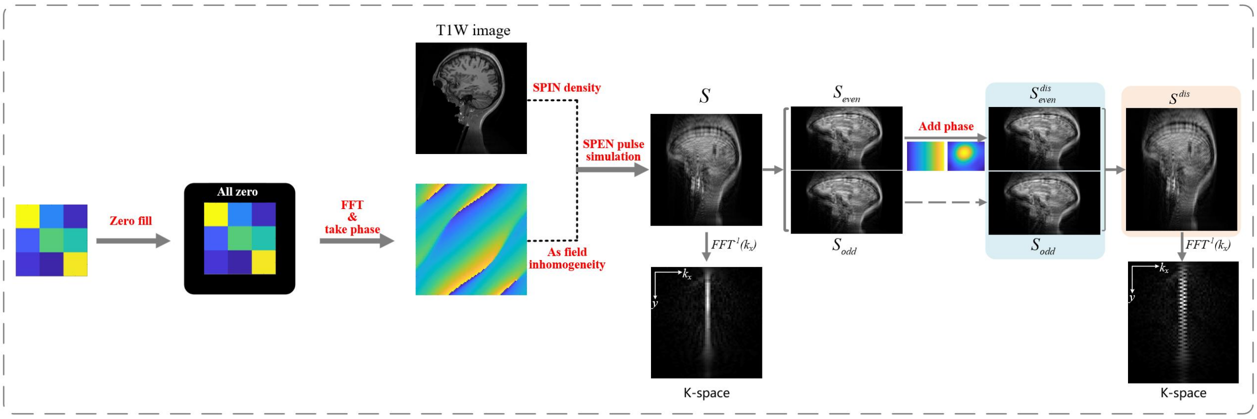


Figure S3. Details of the production process of simulated data. After setting the parameters of the SPEN pulse sequence used in the simulation, the T1w anatomical images of the human brain were sampled using the SPEN sequence, and FT along the RO direction was performed to obtain low-resolution SPEN images S. Then, odd and even echoes of S were separated and random linear/nonlinear phases were applied to the even echo images S_{even}. Phase-distorted even echo images S_{even}^{dis} and the original odd echo images S_{odd} were used as the simulated data for RERSM-net. Finally, S_{even}^{dis} and S_{odd} were recombined to obtain full phase-distorted SPEN images S^{dis} as the simulated data for the conventional method. Because HCP T1w images contained only magnitude and no phase information, to obtain an actual k-space, a phase for T1w images was generated. This was performed by creating a 3x3 matrix of random numbers. This 3x3 matrix was zero padded to the corresponding T1w image size and Fourier transformed. Since only elements at the center of this matrix corresponding to an area of 3x3 were distinct from zero, Fourier transformed matrix contained only low-frequency information equivalent to a smooth phase. The final image used as an input to simulation was obtained by multiplying T1w image with complex exponential of generated phase map. To obtain image S, SPEN pulse sequence depicted in Figure 1(a) was simulated with corresponding acquisition and encoding parameters: FOV=4x4 cm2, sampling matrix=256x256 (ROxPE), effective TE=36 ms, TR=4 seconds, R value of chirp pulse= 400, pulse length=18 ms. 32 spins per voxel were used to avoid discontinuities and the simulations were performed in Matlab using Spintool package (Tal, A (2020). Visual Display Interface (VDI) [Computer Software]. Retrieved from http://www.vdisoftware.net).

The structure of U-net

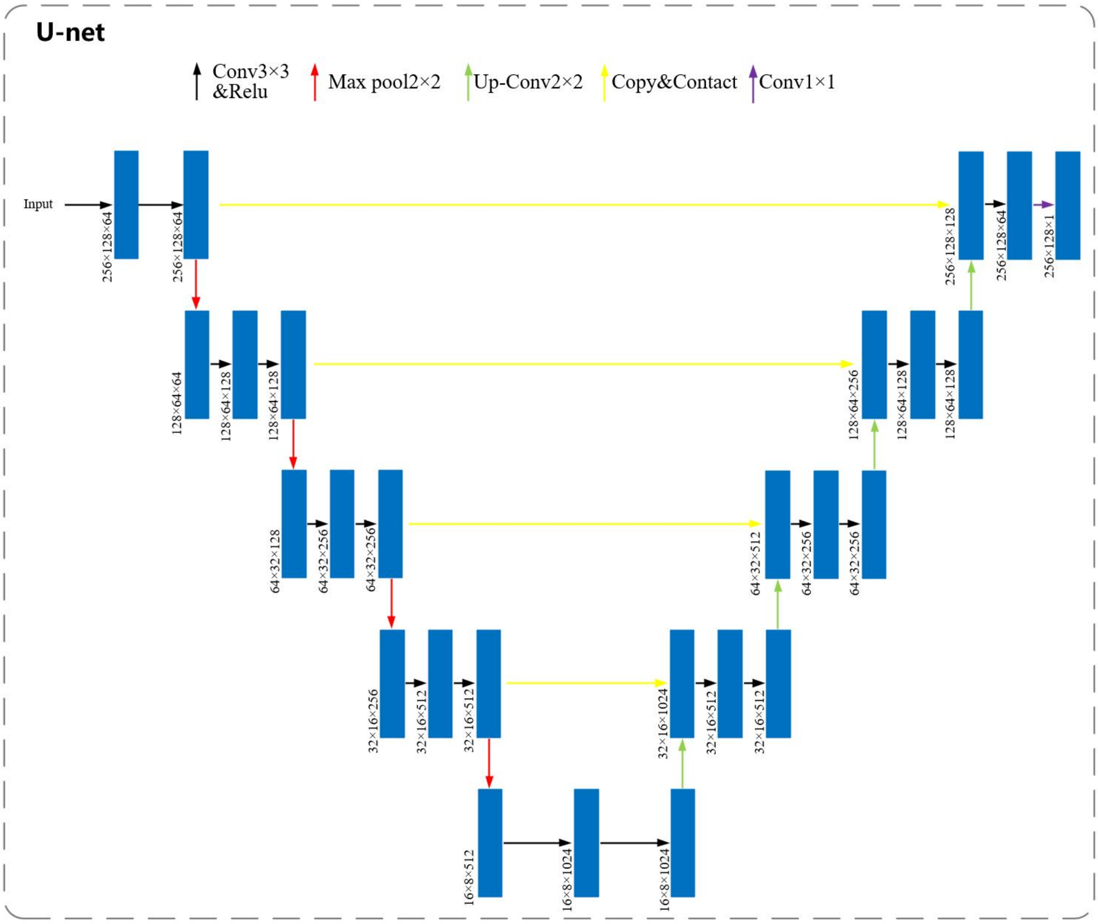
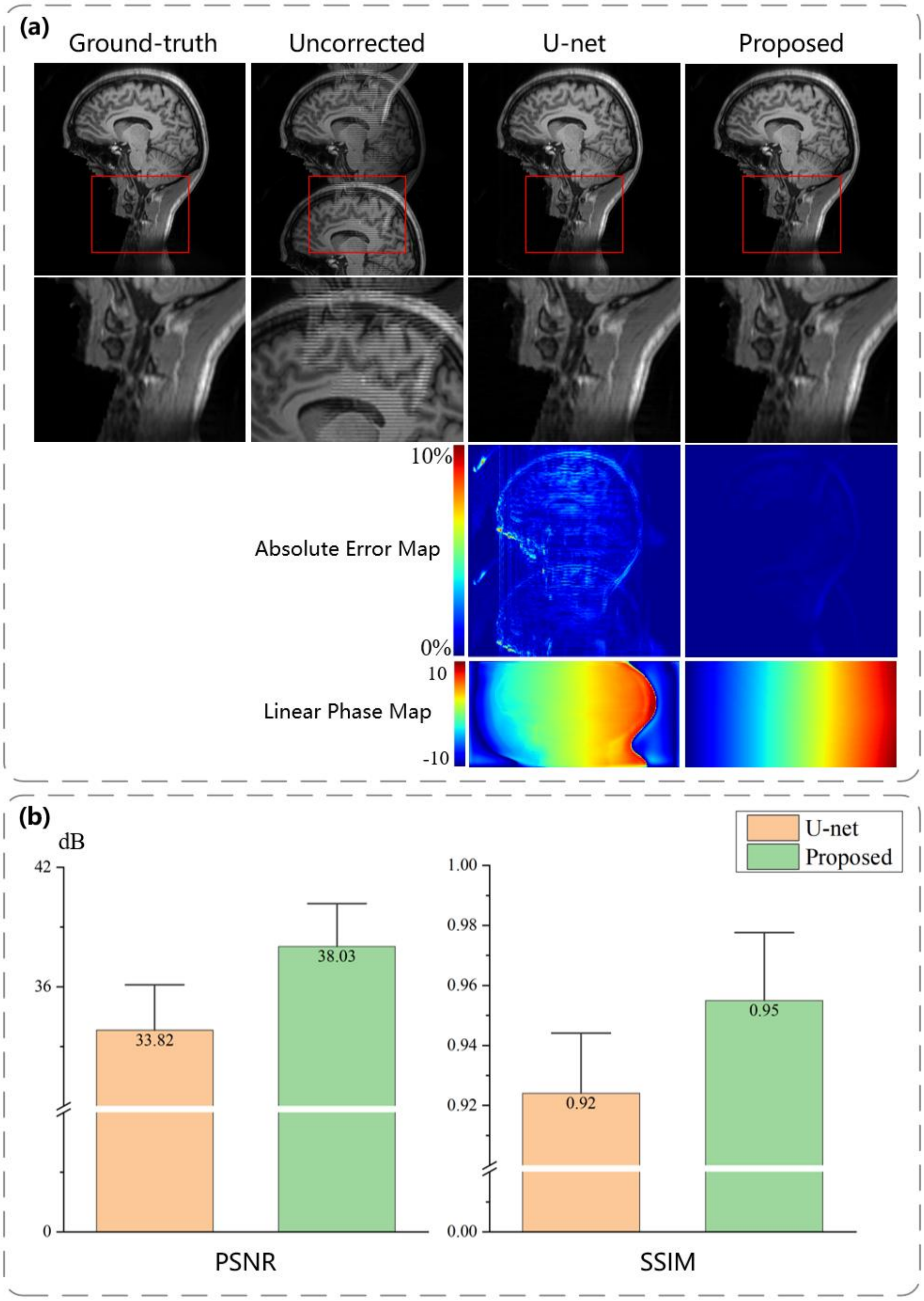
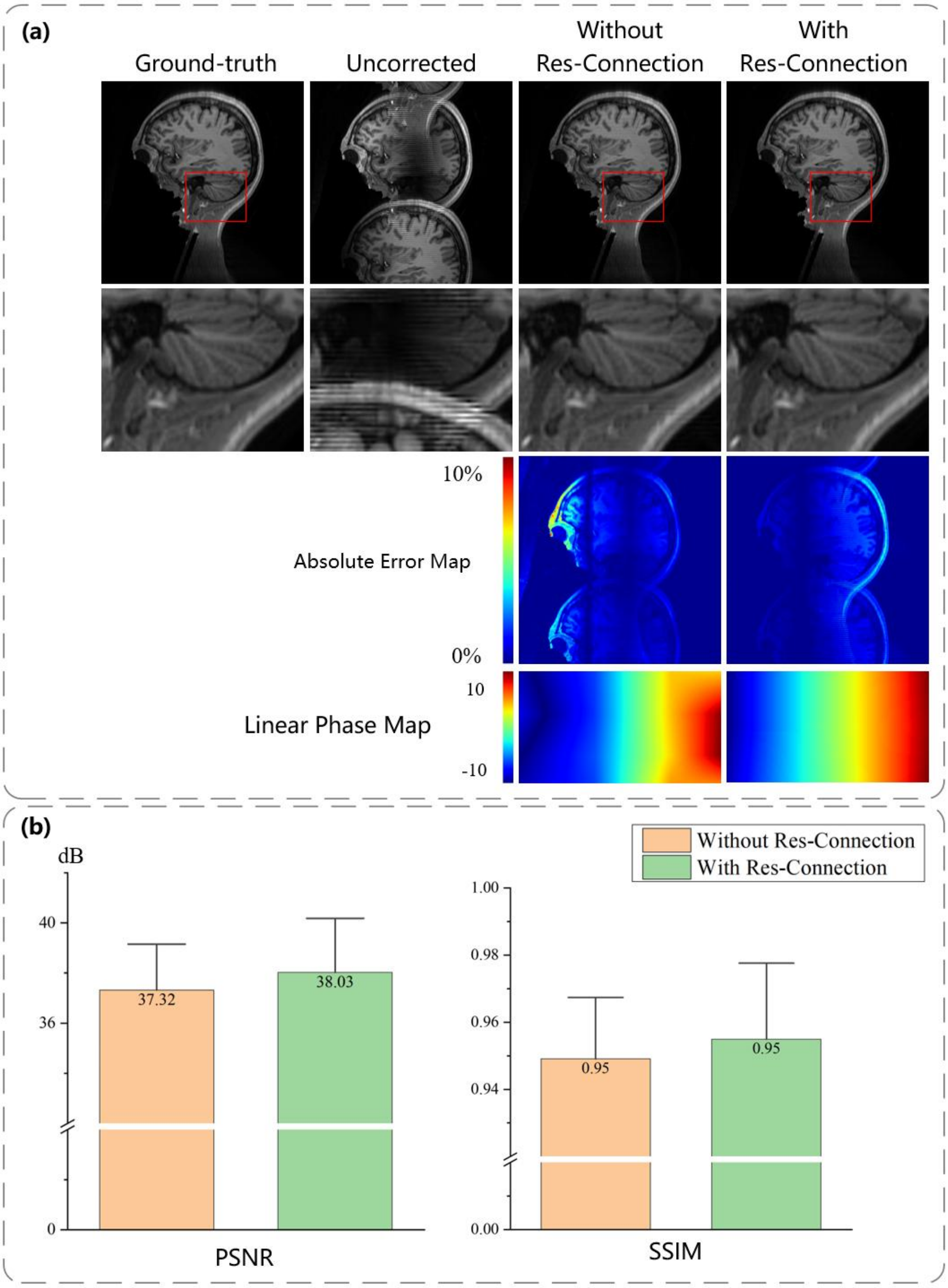


Figure. **S4** The detailed structure of U-net used for comparative experiment.

Result



FigureS5 Comparison of the proposed RERSM-net and U-net. (a) The first row from left to right shows the uncorrected ghost image, ground truth image, and ghost-corrected images by U-net and the proposed RERSM-net, respectively. The second row shows the zoomed region of the first row's images. The third row shows the absolute error maps. The fourth row shows the phase difference maps. (b) Quantitative results of PSNR, SSIM for various comparison methods.



FigureS6 The comparison between the proposed RERSM-net and the ablation experiment with residual structure removed by the network (a) shows the ground truth image and uncorrected ghost image, the corrected images of the RERSM-net without residual structure and the complete RERSM-net are presented in the first row from left to right. The second row shows the zoom area of the first row image. The third line displays the absolute error map (the differences between the Nyquist-ghost corrected image and ground truth image). The fourth line shows the phase difference plot. (b) Quantitative results of PSNR and SSIM for various comparison methods.

Table S1. The pulse sequence parameters.

	RARE	EPI	SPEN
Phantom	FOV = 35×35 mm^2 Matrix = 128×128 Effective TE = 24 ms Rare Factor = 8 TR = 2000 ms Slice thickness = 2 mm	FOV = 35×35 mm^2 Matrix = 96×96 Effective TE = 52.91 ms TR = 2000 ms Slice thickness =2 mm	FOV = 35×35 mm^2 Matrix = 96×96 Effective TE = 59.89 ms TR = 2000 ms Slice thickness =2 mm Rvalue = 120 Pulse length = 18.43 ms
Orange	FOV = 50×50 mm^2 Matrix = 128×128 Effective TE = 40 ms Rare Factor = 8 TR = 2000 ms Slice thickness =2 mm	FOV = 50×50 mm^2 Matrix = 96×96 Effective TE = 52.91 ms TR = 2000 ms Slice thickness = 2 mm	FOV = 50×50 mm^2 Matrix = 96×96 Effective TE = 59.89 ms TR = 2000 ms Slice thickness = 2 mm Rvalue = 120 Pulse length = 18.43 ms
Cucumber	FOV = 40×40 mm^2 Matrix = 128×128 Effective TE = 40 ms Rare Factor = 8 TR = 2000 ms Slice thickness = 2 mm	FOV = 40×40 mm^2 Matrix = 96×96 Effective TE = 52.91 ms TR = 2000 ms Slice thickness = 2 mm	FOV = 40×40 mm^2 Matrix = 96×96 Effective TE = 59.89 ms TR = 2000 ms Slice thickness = 2 mm Rvalue = 120 Pulse length = 18.43 ms
In vivo rat	FOV = 40×40 mm^2 Matrix = 128×128 Effective TE = 20 ms Rare Factor = 4 TR = 2000 ms Slice thickness = 2 mm	FOV = 30×30 mm^2 Matrix = 96×96 Effective TE = 67.75 ms TR = 2000 ms Slice thickness = 2 mm	FOV = 30×30 mm^2 Matrix = 96×96 Effective TE = 61.66 ms TR = 2000 ms Slice thickness = 2 mm Rvalue = 100 Pulse length = 19.53 ms

Table S2. The details of the used U-net in this study.

	Layer name	Output size			Layer name	Output size	
Encoder1	Conv1_1/ReLU	[256×128, 64]	Conv 3×3	**Decoder1**	Up-conv6_1/ReLU	[32×16, 512]	Up-Conv 2×2
	Conv1_2/ReLU	[256×128, 64]	Conv 3×3		Copy/Concat	[32×16, 1024]	-
	Max pool1	[128×64, 64]	Max pool 2×2		Conv6_2/ReLU	[32×16, 512]	Conv 3×3
Encoder2	Conv2_1/ReLU	[128×64, 128]	Conv 3×3		Conv6_3/ReLU	[32×16, 512]	Conv 3×3
	Conv2_2/ReLU	[128×64, 128]	Conv 3×3	**Decoder2**	Up-conv7_1/ReLU	[64×32, 256]	Up-Conv 2×2
	Max pool2	[64×32, 128]	Max pool 2×2		Copy/Concat	[64×32, 512]	-
Encoder3	Conv3_1/ReLU	[64×32, 256]	Conv 3×3		Conv7_2/ReLU	[64×32, 256]	Conv 3×3
	Conv3_2/ReLU	[64×32, 256]	Conv 3×3		Conv7_3/ReLU	[64×32, 256]	Conv 3×3
	Max pool3	[32×16, 256]	Max pool 2×2	**Decoder3**	Up-conv8_1/ReLU	[128×64, 128]	Up-Conv 2×2
Encoder4	Conv4_1/ReLU	[32×16, 512]	Conv 3×3		Copy/Concat	[128×64, 256]	-
	Conv4_2/ReLU	[32×16, 512]	Conv 3×3		Conv8_2/ReLU	[128×64, 128]	Conv 3×3
	Max pool4	[16×8, 512]	Max pool 2×2		Conv8_3/ReLU	[128×64, 128]	Conv 3×3
Encoder5	Conv5_1/ReLU	[16×8, 1024]	Conv 3×3	**Decoder4**	Up-conv9_1/ReLU	[256×128, 64]	Up-Conv 2×2
	Conv5_2/ReLU	[16×8, 1024]	Conv 3×3		Copy/Concat	[256×128, 128]	-
					Conv9_2/ReLU	[256×128, 64]	Conv 3×3
					Conv9_3/ReLU	[256×128, 1]	Conv 3×3

List of figures

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