Supplemental material

Accelerating susceptibility-weighted imaging with deep learning by complex-valued convolutional neural networks (ComplexNet): Validation in clinical brain imaging

Network architecture

As shown in Figure 1, the ComplexNet cascades 5 convolutional neural network (CNN) modules and 5 data consistency layers. In each CNN module, four complex convolutional layers, with a 3 × 3 kernel size and 128 feature maps, are sequentially applied to extract abundant features. Then, a complex convolutional layer with a 1 × 1 kernel size is used to reconstruct the residual images. In this study, the complex convolutional layer is developed based on the distributive property of convolution. Let $\mathbf{X} = \mathbf{X}_r + i\mathbf{X}_i$ denotes a complex input, and $\mathbf{W} = \mathbf{W}_r + i\mathbf{W}_i$ denotes a complex convolutional kernel, then the complex convolution between **X** and **W** can be represented as:

$$\mathbf{W} * \mathbf{X} = (\mathbf{W}_r + i\mathbf{W}_i) * (\mathbf{X}_r + i\mathbf{X}_i) = (\mathbf{W}_r * \mathbf{X}_r - \mathbf{W}_i * \mathbf{X}_i) + \boldsymbol{i}(\mathbf{W}_r * \mathbf{X}_i + \mathbf{W}_i * \mathbf{X}_r) \quad (1)$$

Using Equation 1, the complex convolution can be split into 4 separate real-valued convolutions and implemented using the commonly used deep learning toolbox (e.g., TensorFlow). The complex-valued convolutional layer has half as many parameters compared to its real-valued counterpart [1].

Each complex convolutional layer, except for the last layer, is followed by a complex-valued activation function. We adopt CReLU function as the complex-valued activation function because it performed the best over the other activation functions [1]. The CReLU function applies separate rectified linear units (ReLUs) on real and imaginary components of a complex-valued input and adds them, which can be defined as:

$$\text{CReLU}(\mathbf{X}) = ReLU(\mathbf{X}_r) + iReLU(\mathbf{X}_i) \quad (2)$$

where $ReLU$ denotes rectified linear unit, $\mathbf{X}_r$ and $\mathbf{X}_i$ denote the respective real and imaginary components of **X**.

Implementation and training

In Supplementary Fig. 1**,** we investigated the reconstruction performance of ComplexNet with respect to different parameter settings on the validation dataset. The impact of batch size on performance was evaluated by fixing the learning rate to 0.0002. We can see that the batch size of 8 gives the best performance in Supplementary Fig. 1a. Then, the impact of learning rate on performance was evaluated by fixing the batch size to 8. Supplementary Fig. 1b shows that the learning rate of 0.0002 provides the highest performance. Therefore, we set batch size to 8 and learning rate to 0.0002 in the network training process.

References

1. Cole E, Cheng J, Pauly J, et al. Analysis of deep complex-valued convolutional neural networks for MRI reconstruction and phase-focused applications. Magn Reson Med 2021;86(2):1093–1109.

Supplemental Table 1 Scoring criteria used for evaluation of fully sampled and ComplexNet approaches

Score	Overall Image Quality	Signal-to-Noise Ratio	Sharpness	Artifacts
1	Nondiagnostic	All structures appear to be too noisy.	Some structures are not sharp on most images.	There are all three artifacts (aliasing, signal loss regions, or cartoonish appearance) on all images.
2	Limited	Most structures appear to be too noisy	Most structures are sharp on some images.	There are two types of artifacts among (aliasing, signal loss regions, or cartoonish appearance) on all images.
3	Diagnostic	Few structures appear to be too noisy on most images.	Most structures are sharp on most images.	There is no aliasing, signal loss regions, or cartoonish appearance on a few images.
4	Good	Few structures appear to be too noisy on a few images.	All structures are sharp on most images.	There is no aliasing, signal loss region, or cartoonish appearance on most images.
5	Excellent	There is no noticeable noise on any of the images.	All structures are sharp on all images.	There is no aliasing, signal loss region, or cartoonish appearance on any image.

ComplexNet, complex-valued convolutional neural network.

Supplementary Table 2 Comparison of the detection of CMBs between the fully sampled and ComplexNet approaches at R = 5 and R = 8

	Fully sampled	ComplexNet (R = 5)	*p* value	ComplexNet (R = 8)	*p* value
Presence of CMBs					
Overall	34/70	34/70	1.000	34/70	1.000
Reader 1	17/35	17/35	1.000	17/35	1.000
Reader 2	17/35	17/35	1.000	17/35	1.000
No. of CMBs					
Infratentorial					
Overall	59 (0-13)	60 (0-13)	0.655	56 (0-13)	0.083
Reader 1	30 (0-13)	31 (0-13)	0.317	28 (0-13)	0.157
Reader 2	29 (0-12)	29 (0-13)	1.000	28 (0-12)	0.317
Deep					
Overall	120 (0-21)	128 (0-22)	0.198	125 (0-23)	0.538
Reader 1	63 (0-21)	65 (0-21)	0.589	60 (0-21)	0.453
Reader 2	57 (0-19)	63 (0-22)	0.202	65 (0-23)	0.107
Lobar					
Overall	87 (0-26)	90 (0-26)	0.429	93 (0-28)	0.132
Reader 1	45 (0-26)	46 (0-26)	0.655	47 (0-27)	0.317
Reader 2	42 (0-25)	44 (0-26)	0.480	46 (0-28)	0.257

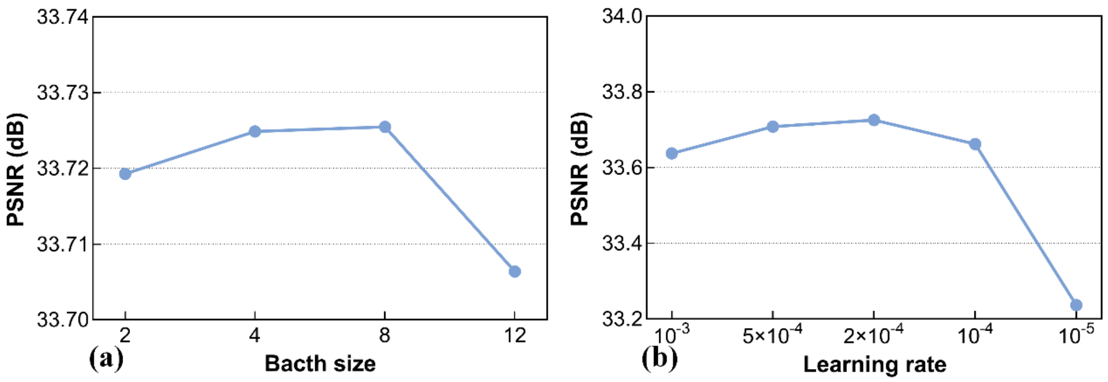
Note: *p* values were calculated by using McNemar test for the presence of CMBs and Wilcoxon signed rank test for the number of CMBs. Presence of CMBs was presented as the number of the participants with CMBs/total number of participants. No. of CMBs was presented as total number of CMBs (range) according to MARS. *CMBs*, cerebral microbleeds; *ComplexNet*, complex-valued convolutional neural network; *MARS*, Microbleed Anatomical Rating Scale; *R*, acceleration rate

Supplementary Table 3 Interobserver agreement for the detection of CMBs on the fully sampled and ComplexNet approaches at R = 5 and R = 8

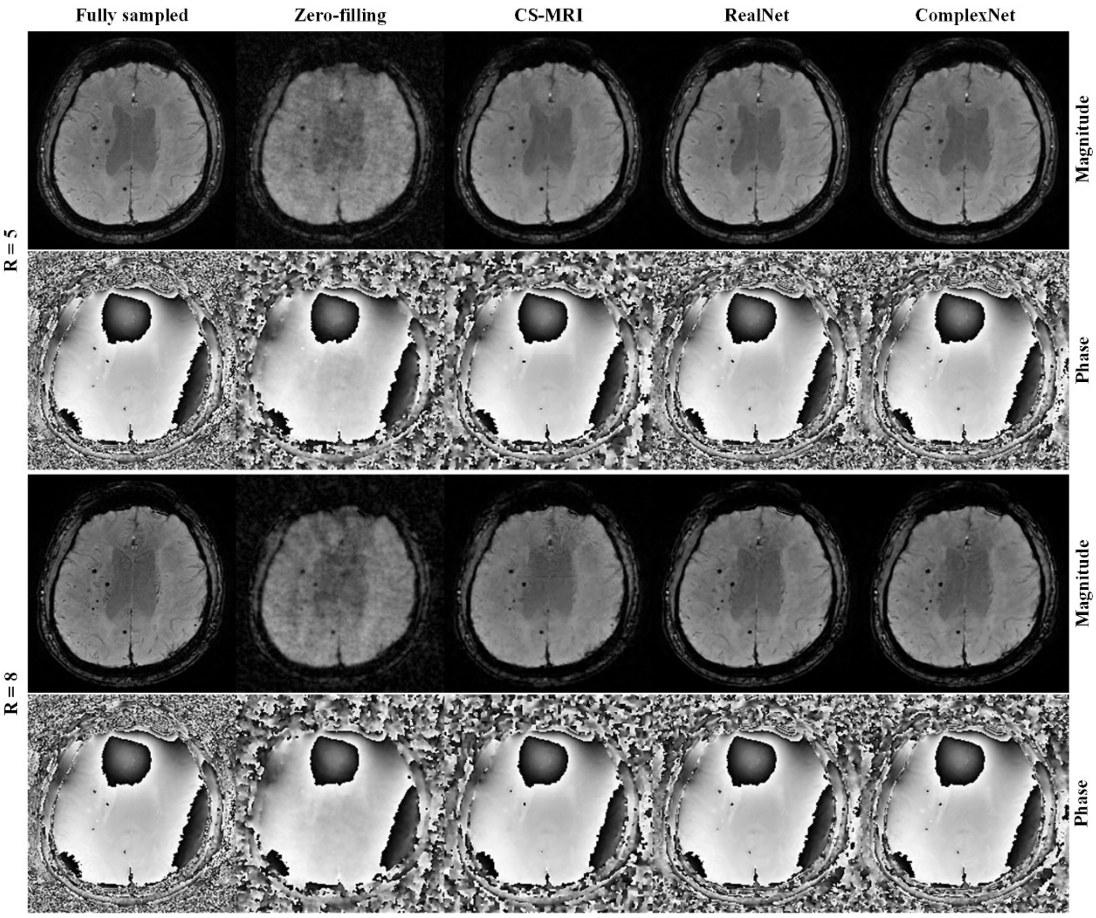
	Kappa value/ intraclass correlation coefficient (95% confidence interval)
Presence of CMBs	
Fully sampled	1.000
ComplexNet (R = 5)	1.000
ComplexNet (R = 8)	1.000
No. of CMBs	
Infratentorial	
Fully sampled	0.992 (0.984-0.996)
ComplexNet (R = 5)	0.990 (0.980-0.995)
ComplexNet (R = 8)	0.995 (0.989-0.997)
Deep	
Fully sampled	0.993 (0.985-0.996)
ComplexNet (R = 5)	0.990 (0.981-0.995)
ComplexNet (R = 8)	0.988 (0.977-0.994)
Lobar	
Fully sampled	0.998 (0.995-0.999)
ComplexNet (R = 5)	0.999 (0.997-0.999)
ComplexNet (R = 8)	0.997 (0.994-0.998)

CMBs, cerebral microbleeds; *ComplexNet*, complex-valued convolutional neural network; *R*, acceleration rate

Supplementary Fig. 1 Average reconstruction performance comparison with different parameter settings. Average PSNR of ComplexNet at R = 8 on the validation data with respect to batch size (a) and learning rate (b).



Supplementary Fig. 2 The corresponding reconstructed magnitude and phase images of Figure 2 obtained using the fully sampled, zero-filling, CS-MRI, RealNet, and ComplexNet at R = 5 and R = 8. *ComplexNet*, complex-valued convolutional neural network; *CS-MRI*, compressed sensing MRI; *R*, acceleration rate; *RealNet*, real-valued convolutional neural network



Supplementary Fig. 3 Noninferiority testing of ComplexNet to the fully sampled method in terms of image quality scores. Error bars show the two-sided 95% confidence intervals of the difference in image quality scores between ComplexNet at R = 5 (a) and R = 8 (b) and the fully sampled method.