# GRAPPA parallel imaging performance of Siemens 32ch vs. 64ch receiver coils at Prisma 3T scanner; Maximum acceleration factors for SMS MB EPI

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## ABSTRACT

Parallel imaging is required for acquisition of fast MRI, for example, functional MRI and diffusion weighted tensor imaging using echo planar imaging sequence. Two-dimensional acceleration is common in modern simultaneous multiple slice multi-band EPI, that is, in phase encoding and slice selection direction. Performance of parallel imaging can be improved by using multiple channel receiver coil. The maximum acceleration factor is dependent of applied receiver coil and parallel imaging encoding method. In this study, Siemens 32ch and 64ch multi-channel receiver coils are compared in parallel imaging performance, and the maximum acceleration factors are suggested for SMS MB EPI sequence.

## ABBREVIATION/DEFINITION

PI - Parallel imaging
GRAPPA – Generalized autocalibrating partial parallel acquisition; reconstruction method
Slice-GRAPPA – GRAPPA reconstruction through slices; reconstruction
ACS – Autocalibration signal
CAIPIRINHA - Controlled aliasing in parallel imaging results in higher acceleration
CAIPI – Controlled aliasing in parallel imaging
SMS – Simultaneous multiple slice; acquisition
MB – Multi-band
AF – Acceleration factor
iPAT – GRAPPA acceleration factor in 2D MRI
FOV shift – Number of slice encoding
GRAPPA kernel – Small window for GRAPPA reconstruction convolution
1D GRAPPA – Accelerated GRAPPA in phase encoding
2D GRAPPA – Accelerated GRAPPA in phase and slice encoding
G-factor – Coil geometry penalty factor in parallel imaging
SNR – Signal to noise ratio
SNR-unit – GRAPPA reconstruction in SNR unit
SNR-retained – Ratio of SNR-unit of PI to full-sampled imaging
MPRAGE – Magnetization prepared rapid gradient echo
SPGR – Spoiled gradient recalled acquisition in the steady state
TR – Repetition time
TE – Echo time
TI – Inversion time
FOV – Field of view
RO – Readout
PE – Phase encoding
SE – Slice encoding
A – Anterior

P – Posterior
H – Head
F – Foot
L – Left
R – Right
A-P – Anterior to posterior direction
H-F – Head to foot direction

## INTRODUCTION

Fast MRI acquisition is critical for dynamic and long-scan-time imaging, particularly for functional and diffusion-weighted tensor MRI (fMRI and DWI). With the advancement of multiple channel receivers, the scan time could be dramatically reduced by subsampling in image acquisition following phase encoding or slice selection direction using, so called, parallel imaging (PI) such as GRAPPA and SENSE. While the scan time can be reduced, the image SNR decreases mainly due to smaller sampling of the data than conventional full-sampling acquisition. Therefore, the estimation of SNR change by subsampling factor, that is, acceleration factor (AF) is necessary. Particularly, for fMRI requiring high speed volume scan, less than 1sec for sampling of whole brain volume, maximum AF needs to be selected for the given multi-channel receiver coil to take advantage of filtering out uninterested physiology noises.

Siemens 32ch and 64ch receiver coils are available in MR Research Center (MRRC) at Radiology, UPMC, University of Pittsburgh. 32ch coil is designed for only brain imaging while 64ch coil is for brain and neck & c-spine. MR image quality could be different for the applied coil at different imaging conditions such as head position in the coil and PI acceleration factors. Because multi-channel coil consists of many small coil loops and each loop operates as a small surface coil, MR image quality, e.g., SNR could be affected by distance between imaging object (e.g., brain tissue) and the coil loop in conventional acquisition; the closer location of object to coil loop will make higher signal. On the other hand, the coil geometry and numbers will decide the performance of parallel imaging; maximal AF is determined to achieve acceptable SNR through the coil g-factor.

GRAPPA acquisition and reconstruction in k-space is a representative PI method, its g-factor and SNR-unit maps can be calculated [1-3]. In GRAPPA acquisition, two dimensional AFs can be applied at same time during acquisition of echo train in EPI. Typical AF is in-plane GRAPPA factor, i.e., iPAT while simultaneous multiple slice (SMS) multi-band (MB) is in slice selection. Blipped-controlled aliasing in parallel imaging results in higher acceleration (CAIPHRINA) EPI scan was developed to improve the reconstruction quality [4]. fMRI SNR could be changed by multi-channel coil, e.g., 12ch vs. 32ch vs. 64ch and AF, e.g., MB 2 vs 4 [4-6].

In this report, the performance of three PI (1D GRAPPA, 2D GRAPPA, and SMS slice-GRAPPA) is investigated for various acceleration factors and the acceleration directions for 32ch and 64ch coil. The maximum AFs, i.e., multiband (MB) factor and GRAPPA factor (iPAT) for two coils are investigated.

## METHODS AND MATERIALS

All MR image and data were acquired from Siemens Prisma 3T scanner using 32ch and 64ch receiver coil. A Siemens cylindrical phantom and a human subject head were scanned. The phantom and subject were positioned in vertical center of the coil as much as possible, and the top vertex was set to be touched to the coil plastic frame.

For the measurement of image SNR, same subject was scanned with MPRAGE sequence using 32ch and 64ch coil in same session; TR/TE/TI=1520/3.17/800ms, matrix size=256x256x192, sagittal slice, and FOV=256x256x192 (read-out[RO] x phase-encoding[PE] x slice-encoding[SE]). Two images were co-registered each other in pre-processing, and the noise was measured in the image corner regions and the image-space SNR was measured by the ratio of pixel intensity to the noise. SNR sensitivity map was measured by the ratio of two image SNR maps, that is, [image SNR map of 32ch]/[image SNR map of 64ch].

PI performances were calculated by simulation of 1D GRAPPA, 2D GRAPPA, and SMS slice-GRAPPA using full-sampled k-space data. The full-sampled MR k-space data were subsampled in slice selection or/and phase encoding direction for a PI simulation, which is similar to slice acceleration and in-plane GRAPPA acceleration in SMS MB EPI sequence. All PI data are reconstructed by GRAPPA algorithm. As PI GRAPPA performance indices, g-factor, SNR-unit, SNR-retained (i.e., the ratio of 'SNR of subsampled data' to 'SNR of full-sampled data') maps were calculated.

The reference full-sampled data of a phantom and a human head was acquired with full-sampling by using 3D SPGR (TR/TE=500/2.87ms, matrix size=96x96x72, sagittal slice, FOV=220x220x165 [ROxPExSE], FOV set to iso-center) and MPRAGE sequence (TR/TE/TI=1520/3.17/800ms, matrix size=256x256x192, sagittal slice, and FOV=256x256x192 [ROxPExSE]), respectively. Noise covariance matrix for a coil was also measured from noise scan embedded in the sequence. The raw k-space data were saved and used for PI GRAPPA simulation experiments. Subsampling in k-space domain was done for 1D GRAPPA in phase encoding (A-P in transversal and H-F in sagittal slice imaging), SMS-GRAPPA in phase encoding (A-P), and 2D GRAPPA in phase encoding and slice encoding (A-P and H-F). Simulation of SMS MB GRAPPA acquisition was done as follows; (1) multi-band selected slices were FOV shifted (or CAIPI encoded in slice selection) with given FOV shift value, (2) summation of the FOV shifted multi-band slices, and (3) k-space subsampling in phase encoding for in-plane GRAPPA. The slice-GRAPPA and in-plane GRAPPA reconstruction was done, (1) in-plane GRAPPA for multi-band slices data in kx-ky space and (2) slice-GRAPPA was performed for deconvolution of multi-band slices k-space data into each slice. The SMS MB acquisition or slice-GRAPPA algorithm could be different from those implemented in the scanner, but general idea of algorithm should be same. Main difference between 2D GRAPPA and SMS MB slice-GRAPPA & GRAPPA is if CAIPI encoding is applied or not – the later applies CAIPI encoding to improve the reconstruction performance at high acceleration condition, that is, SNR and unaliasing. Therefore, maximum AFs in SMS MB reconstruction will be higher than those in 2D GRAPPA where no CAIPI encoding is applied.

Analytic g-factor, SNR-unit, and SNR-retained maps were calculated for 1D and 2D GRAPPA, while numeric analysis was applied for slice-GRAPPA using pseudo-replica with repetition of 500 [3].

Parameters of 1D GRAPPA experiment is listed in **Table 1**. The direction of subsampling is A-P or H-F; A-P is typical phase encoding and H-F is slice-selection in conventional SMS MB EPI sequence. GRAPPA in A-P direction indicates in-plane GRAPPA, and that in H-F direction does GRAPPA in slice selection.

Parameters of 2D GRAPPA experiment is listed in **Table 2**. The first subsampling direction is A-P, i.e., phase encoding and the second subsampling is done in H-F direction, that is, slice encoding.

SMS MB slice-GRAPPA and in-pane GRAPPA PI is done for the parameters listed in **Table 3**. SMS direction is H-F direction for slice selection and FOV shift is A-P direction, that is, phase encoding, these settings are operational in SMS MB EPI sequence in the scanner.

**Table 1.** PI acceleration factors for 1D GRAPPA. Kernel size, 4 x 5 (RO x PE) is applied for GRAPPA reconstruction.

| | **In-plane GRAPPA acceleration factor (iPAT)** | | | | | | |
|---|---|---|---|---|---|---|---|
| **A-P dir.** | 1 | 2 | 3 | 4 | 5 | 6 | 8 |
| **H-F dir.** | 1 | 2 | 3 | 4 | 5 | 6 | 8 |
| **ACS lines** | n/a | 24 | 36 | 48 | 60 | 72 | 86 |

**Table 2.** PI acceleration factors for 2D GRAPPA in phase encoding (PE) and slice encoding (SE).

| **SE(H-F)\PE(A-P) AF** | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | n/a | O | O | O |
| 2 | O | O | O | O |
| 3 | O | n/a | n/a | n/a |
| 4 | O | n/a | n/a | n/a |

**Table 3.** PI acceleration factors for SMS slice-GRAPPA experiment. Slice-GRAPPA kernel size is 5 x 5, and in-plane GRAPPA kernel is 2 x 5 (PE x RO).

| **MB factor** | **MB / FOV shift / iPAT acceleration factor** | | | | | | |
|---|---|---|---|---|---|---|---|
| **MB 2** | 2/1/1 | 2/2/1 | 2/2/2 | x | x | x | x |
| **MB 3** | 3/1/1 | 3/2/1 | 3/3/1 | 3/2/2 | 3/3/2 | | |
| **MB 4** | 4/1/1 | 4/2/1 | 4/3/1 | 4/2/2 | 4/3/2 | x | x |
| **MB 5** | 5/1/1 | 5/2/1 | 5/3/1 | 5/2/2 | 5/3/2 | x | x |
| **MB 6** | 6/1/1 | 6/2/1 | 6/3/1 | 6/2/2 | 6/3/2 | x | x |
| **MB 8** | 8/1/1 | 8/3/1 | 8/4/1 | 8/2/2 | 8/3/2 | 8/4/2 | x |

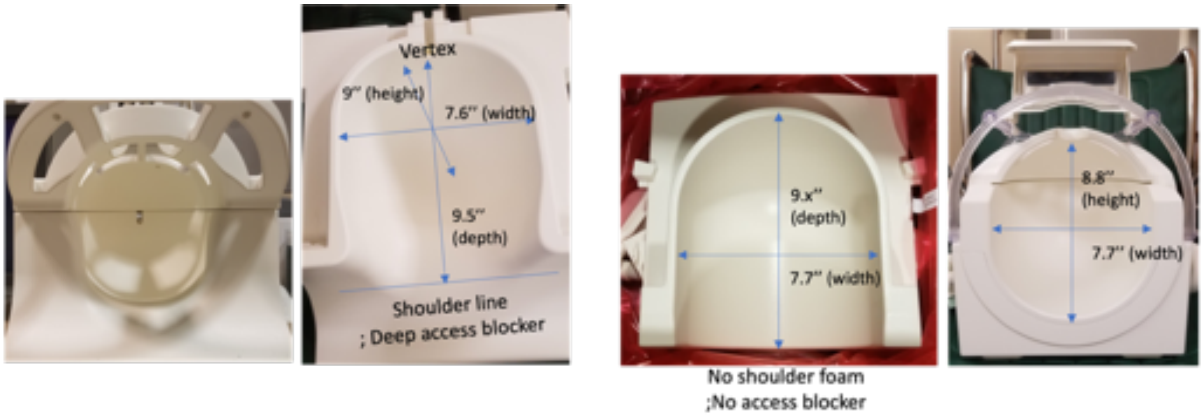
*Note blue parameters are for SMS MB and in-plane GRAPPA.

## RESULTS

There are two main experiments in this study – image-space SNR and PI performance including g-factor, SNR-unit and SNR-retained.

### Coil geometry

64ch coil can cover the head and the neck, most of channels (42? channels) are dedicated for the head coverage and 12? channels are for the neck, while 32ch coil (20ch lower helmet part, 12ch upper helmet part; top plane with 7 elements, a circle of 10 elements, a row of 9 elements and a bottom row of 6 elements [6]) can cover only the head. The dimension of inner volume of two coils are similar each other (**Fig. 1**), that is, 7.6’’(width) x 9’’(height) x 9.5’’(depth) and 7.7’’(width) x 8.8’’(height) x 9.2’’(depth) for 64ch and 32ch coil, respectively. 64ch coil has a little higher upper plastic cap which is helpful for high nose positioning. A big difference between two coils is a shoulder plastic form which could block the head from positioning in deep location of the coil; the shoulder form exists only for 64ch coil. So, with 32ch coil without a shoulder foam, the access to deeper coil position is feasible, which makes closer head vertex positioning to the coil loops possible, particularly for shor-neck and young subjects.



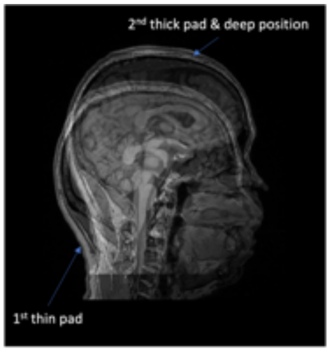
A, 64ch Head/Neck Coil

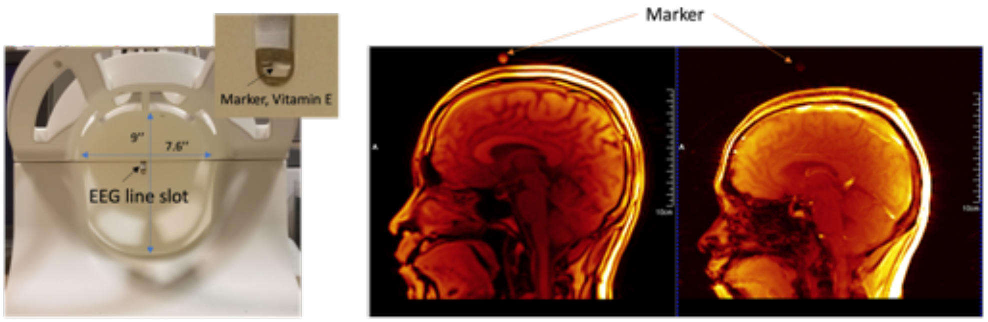
B, 32ch Head Coil

**Fig. 1** Dimension of 64ch (**A**) and 32ch coil (**B**). The inner dimensions of two coils are similar each other.

### Image SNR of MPRAGE sequence

T1 weighted MPRAGE sequence was acquired for a brain structural imaging. Same subject was scanned for each 32ch and 64ch coil in same imaging session. Depending on the posterior head pad, the head location in the coil could be set to deeper coil place (**Fig. 2**). For example, 64ch coil plastic frame is molded with deeper concave shape than 32ch coil. The head should be positioned as much as possible deep location of the coil because most of coil loops are attached backside to the plastic frame, and the closer distance of the imaging object to the coil loop produces higher signal. The position of the head relative to the coil can be visualized in MR image with a Vitamin E capsule (**Fig. 3** left panel). The marker can be easily visualized at Localizer sagittal imaging at iso-center, and so the relative head distance to the coil back can be quickly estimated (**Fig. 3** middle and right panels), so repositioning can be immediately followed prior to main sequence scans. For 32ch coil, the positioning can be done more easily with fully deep positioning the head into the coil.





A, Front view of 64ch coil

B, Sagittal view after vs. before head position

**Fig. 2** (Left first panel) The head positioning can be changed with the used head pad. In this 64ch example, by using thick pad, the head could be set into deeper coil position.

**Fig. 3** (Right two panels) Vitamin E marker on back-hole of 64ch coil. **A**, Front view of the coil showing the marker. **B**, Sagittal localizer image with the marker. The reference marker in the image helps relative-positioning of the head in the coil.

The image SNR was measured from one-subject T1 MPRAGE image by using 32ch and 64ch coils (**Figs. 4 – 6**). Overall SNR patterns of 32ch vs. 64ch MPRAGE images is similar over the whole brain, that is, high SNR around the cortex (red-yellow colored) and low SNR in middle sub-cortical brain region, particularly mid-brain and temporal lobe (blue-cyan colored) (**Figs. 4** and **5**). Although the ratio of two SNR maps shows slightly different SNR sensitivity between two coils, two coils' SNR looks similar over the whole brain (**Fig. 6**) – this small variation could exist for different subjects with their own head geometry. This intrinsic SNR feature will not be improved by adjusting imaging sequence and the parameters, for example, PI acceleration factor.

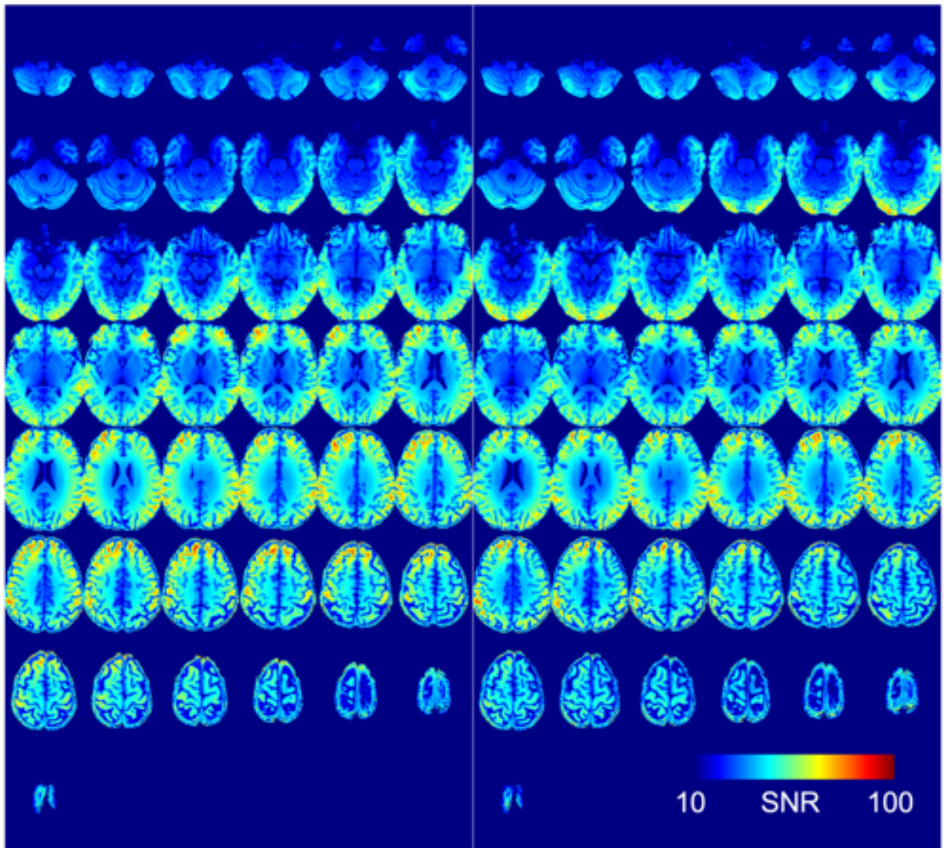


**Fig. 4** Image SNR map of MPRAFGE image in axial slice acquired by 32ch (left panel) and 64ch coil (right panel) - two 3D volume images are co-registered as pre-processing.

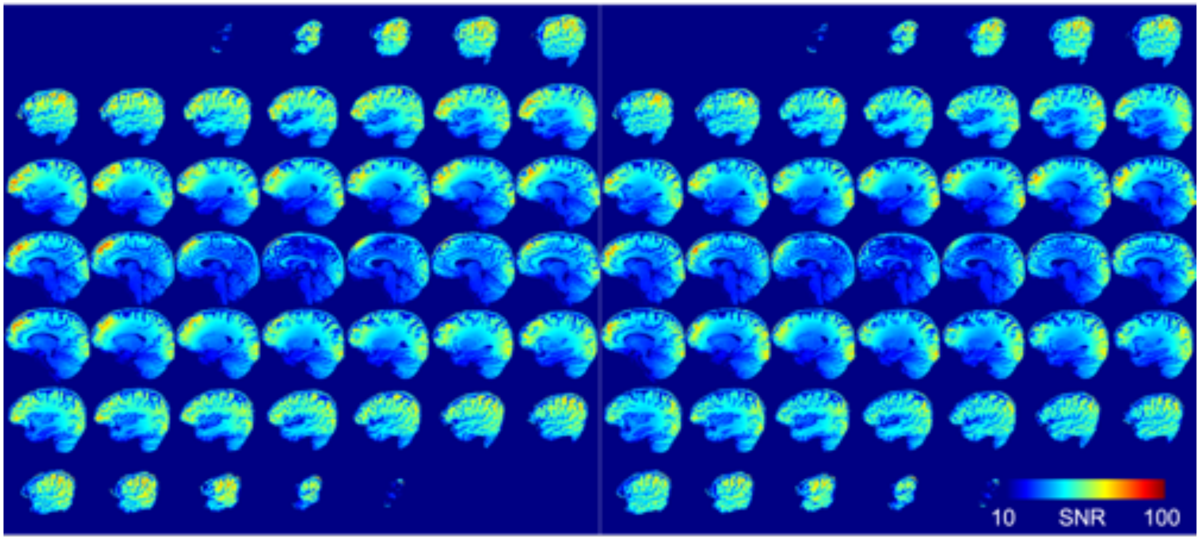


**Fig. 5** Image SNR map of MPRAFGE image in sagittal slice acquired by 32ch (left panel) and 64ch coil (right panel) - two 3D volume images are co-registered as pre-processing. Note that SNR map shows low SNR particularly in the region of temporal lobe, mid and lower brain areas for both coils.

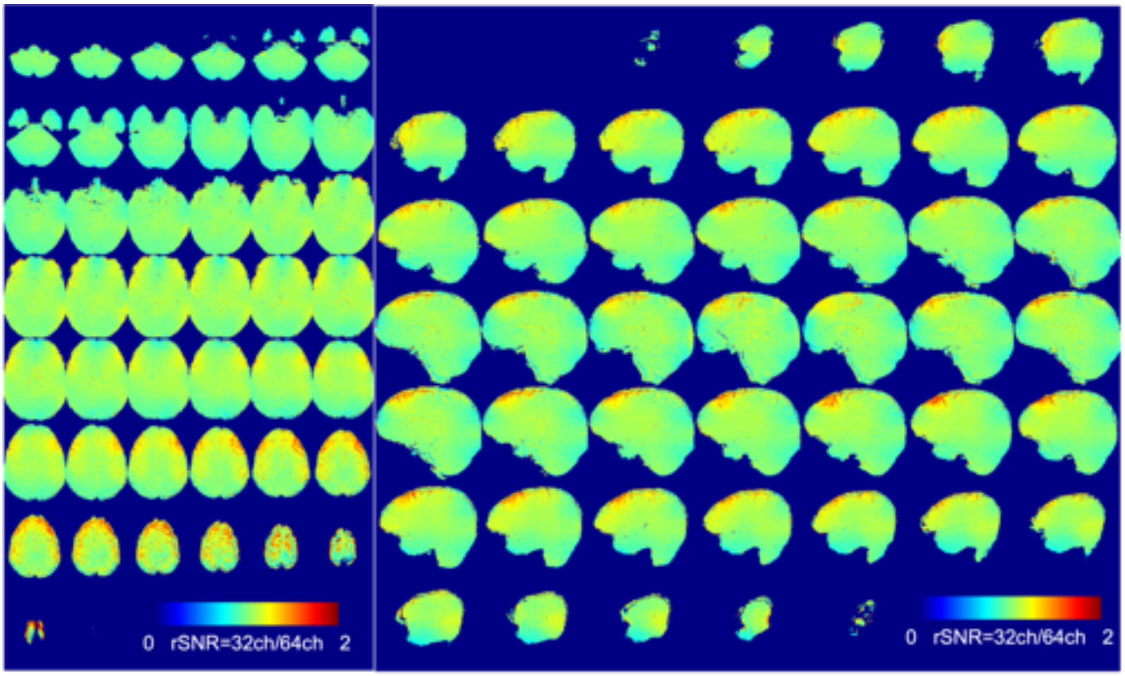
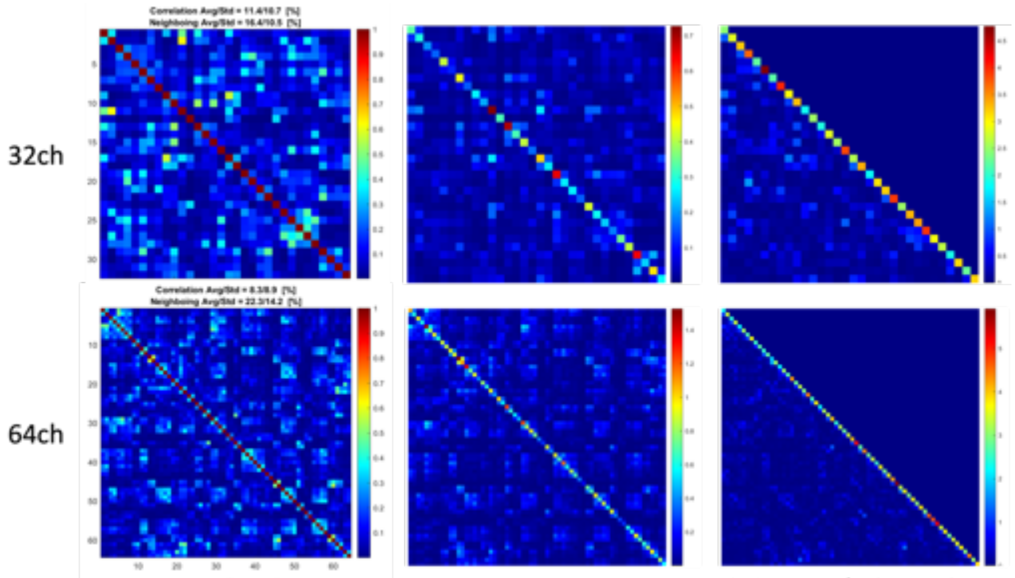


**Fig. 6** Ratio of image SNR map of 32ch vs. 64ch coil. Overall, two coil's SNR maps look similar except very top head – where the subject head touches the coil frame further with 32ch coil than 64ch coil.

### Noise covariance of the coil

The noise covariance matrix in **Fig. 7** shows 32ch is slightly better than 64ch coil because of smaller number of coil loops. The noise matrix will affect PI performance when combined with total number of coil's channels.



A, Normalized noise Covariance & Statistics

B, Noise covariance matrix

C, Decorrelation noise covariance matrix

**Fig. 7** Noise covariance matrix. The noise data is measured in 3D SPGR scan. The noise covariance matrix (**B**) is normalized (**A**) to calculate the statistics. Decorrelation matrix (**C**), i.e., inverse of noise covariance is calculated from the noise covariance matrix, **B**. 32ch coil shows slightly less noise characteristics compared to 64ch coil.

## Parallel imaging performance

PI is done by subsampling of k-space data of full-sampled 3D MPRAGE or SPGR image data. The direction of subsampling (or acceleration) is head-to-foot (H-F) and anterior-to-posterior (A-P) direction, that is, slice selection and phase encoding in a conventional EPI sequence (**Fig. 8**). In GRAPPA simulation, PI with acceleration in slice selection is done with sagittal slice imaging, and that in phase encoding is with transversal slice imaging. PI performance is measured by calculating g-factor, SNR-unit, and SNR-retained map. Through this PI simulation experiment, the maximal/allowable MB factor and GRAPPA acceleration factor (iPAT) are suggested for the 32ch and 64ch coil, respectively.

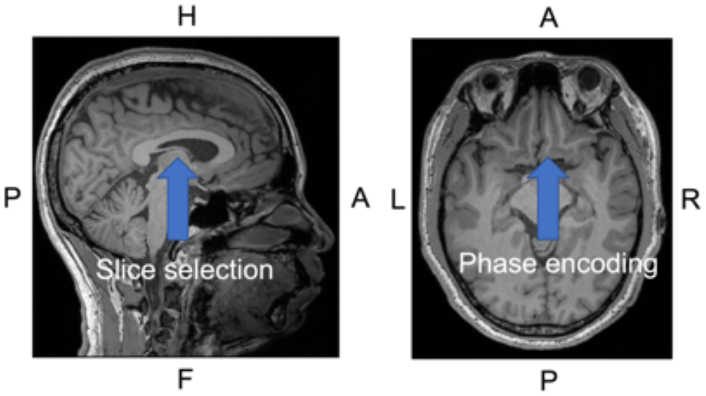


**Fig. 8** Direction of slice selection (H-F) and phase encoding (A-P or P-A) in conventional EPI.

## G-factor map

In **Fig. 9A**, 32ch and 64ch coils show similar pattern of g-factor pattern with various AF factors in slice direction, i.e., H-F (same direction in SMS MB EPI); however, 64ch coil produces more homogeneous distribution compared to 32ch coil (compare AF 3 g-factor maps at different slice in A-P direction). G-factor is greater than 5 with AF > 3, so the maximum straight MB factor in SMS MB MRI shouldn't be more than '3' in slice direction. For PI acceleration in A-P direction (phase encoding in EPI) (**Fig. 9B**), g-factor shows AF 3 is fine, AF 4 produces a little higher g-factor, particularly in lower brain region with 32ch coil; but it seems to be considered for AF 4 with 64ch coil. Therefore, generally straight AF >= 4 in slice-selection and phase encoding is not recommended for both coils.

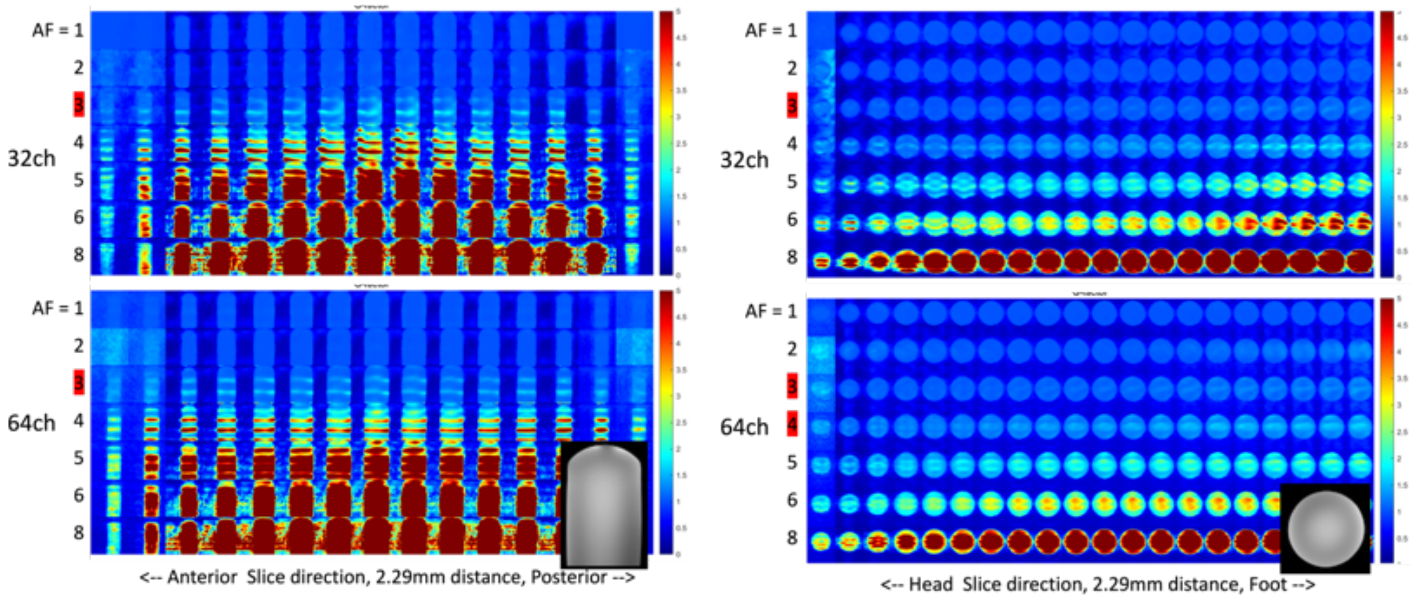


**Fig. 9 A,** GRAPPA g-factor maps of 32ch and 64ch coil in the sagittal imaging for different AFs. Subsampling is done in vertical direction (H-F). The pattern is similar across L-R direction, particularly in 64ch coil. Note that 64ch coil visually shows slightly lower g-factor and better homogeneity in H-F direction. For both coils, AF 2 in H-F is ideal, but maximum AF 3 could be considered, if SNR could be negotiable with other imaging gains. **B,** GRAPPA g-factor maps of 32ch and 64ch coil in the axial imaging. Subsampling is done in vertical axis (A-P). Note that 64ch coil shows lower g-factor and homogeneity in A-P direction at slice axis, particularly lower imaging

position to the foot such as lower brain region. Both coils show acceptable g-factor by AF 2 – 3, but AF 4 could be considered for 64ch coil.

## SNR-unit map

In GRAPPA SNR experiments in **Fig. 10**, the noise can be seen in accelerated direction which is coincident with the pattern in g-factor map. With AF 3 (i.e., straight MB 3 in SMS MB EPI), there is noise band artifact with ~20% SNR compared to reference full-sampled image data in SMS MB EPI. At AF or MB 4, <10% SNR is expected. Note that MB factor in SMS MB EPI is NOT same as straight AF in this 1D GRAPPA – effective AF in slice selection can be reduced by FOV shift CAIPI encoding in SMS MB EPI sequence.

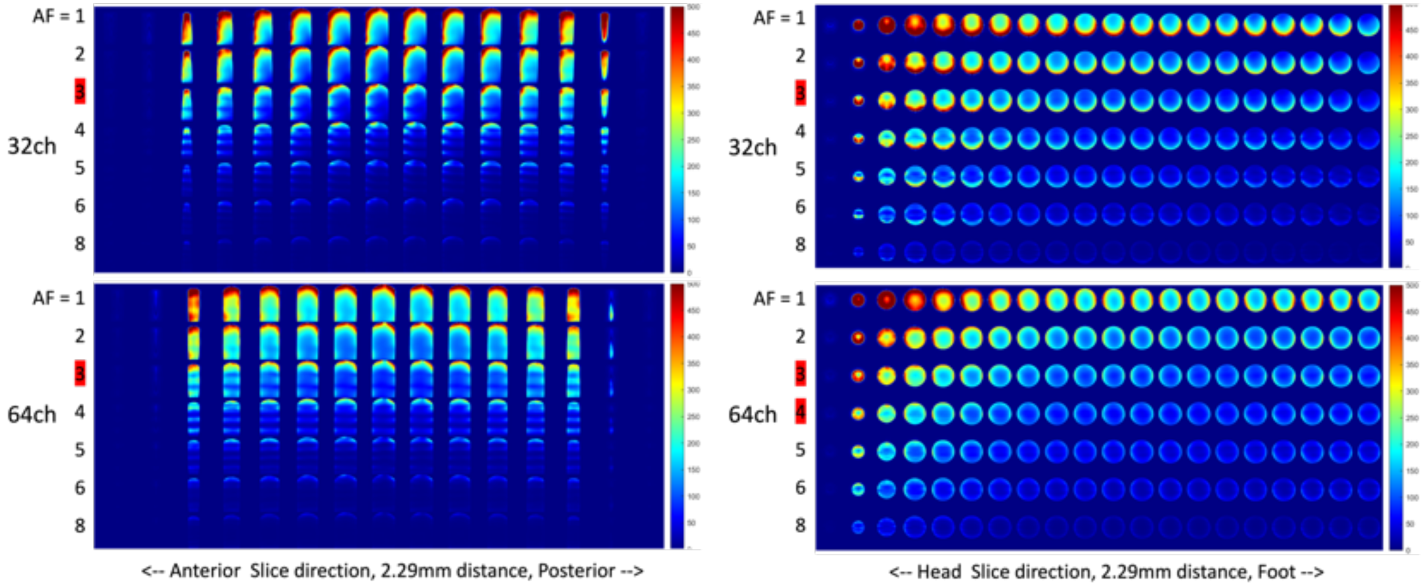


**Fig. 10** SNR-unit map. **A,** GRAPPA SNR unit map of 32ch and 64ch coil. Subsampling is in vertical axis (H-F). Note that the low SNR bands (with 20% SNR compared to full-sampled reference image) in H-F are visible from AF '3'. Therefore, the low SNR band artifacts are expected in SMS MB EPI scan at MB 3. **B,** GRAPPA SNR unit map of 32ch and 64ch coil. Subsampling is in vertical axis (A-P). SNR drop by AF in A-P direction is slightly slower than that by H-F AF.

## SNR-retained map

SNR-retained map is defined by the ratio of SNR maps between PI SNR-unit to reference full-sampled data SNR-unit. So, the normalized SNR-retained is useful to examine SNR decrease with different AF (**Fig. 11**). The 64ch coil SNR-retained map at AF 3 shows greater than 50% - 60%, while 32ch coil does with less than 40% in low SNR bands (**Fig. 11A**). 64ch coil shows slightly high SNR in lower region such as lower brain in PI with A-P acceleration (**Fig. 11B**).

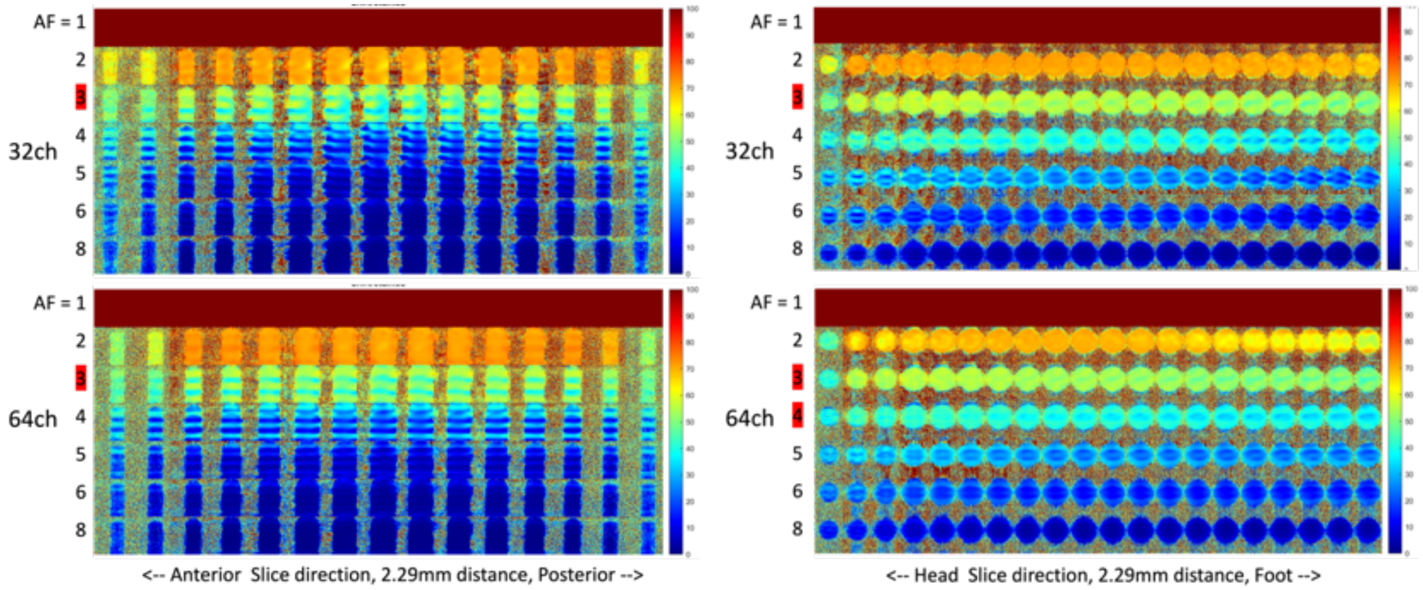


**Fig. 11** SNR-unit map. **A,** SNR-retained map of 32ch and 64ch coil; Subsampling is in vertical axis (H-F). For both coil, AF 4 shows dramatic SNR decrease. **B,** SNR-retained map of 32ch and 64ch coil; Subsampling is in vertical axis (A-P). 32ch coil has similar SNR compared to 64ch in PI with A-P direction; but 64ch shows slightly high SNR in lower brain region.

## GRAPPA image

GRAPPA reconstructed image shows no such large aliasing artifacts visible; but the silhouette of band artifacts in H-F accelerated PI image could be visible, and the noises in PI image with A-P acceleration are visible (**Fig. 12**). The reconstructed image doesn't show the noise as much as in g-factor or SNR-retained maps.

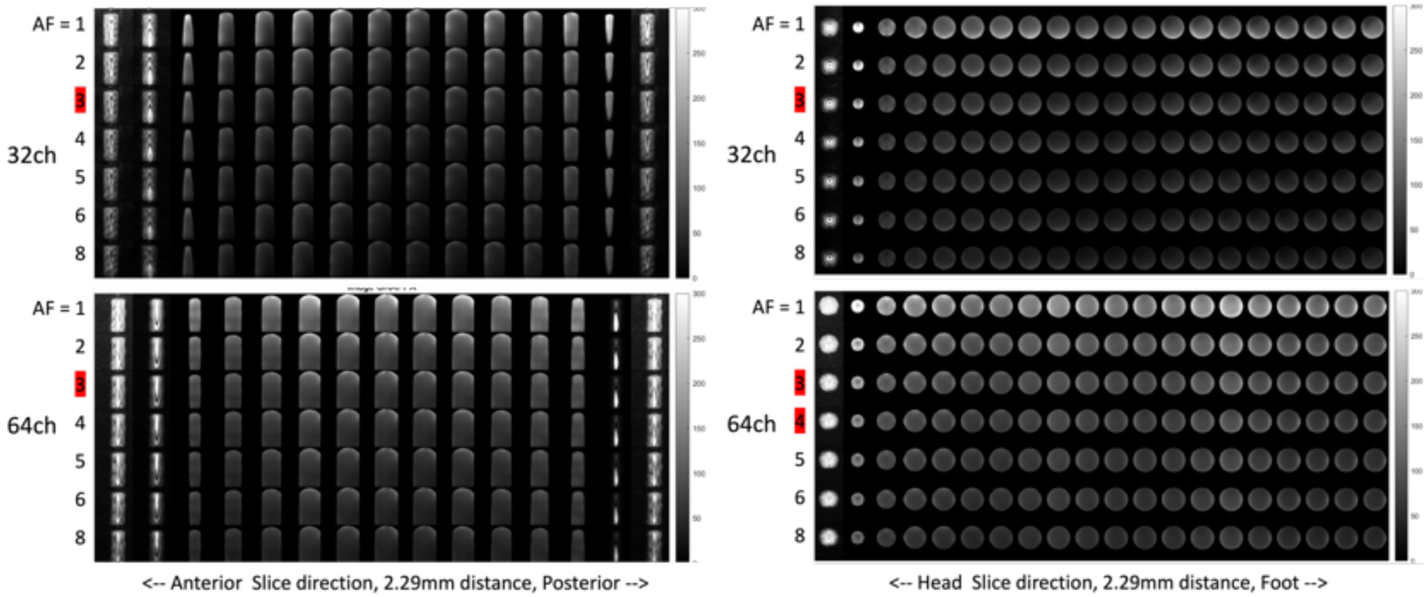


**Fig. 12 A,** GRAPPA image of 32ch and 64ch coil. Subsampling is in vertical axis (H-F). **B,** GRAPPA image of 32ch and 64ch coil. Subsampling is in vertical axis (A-P).

PI performance was further quantified by ROI analysis with mean and standard deviation (**Fig. 13**); ROI is determined by simple image intensity threshold for phantom-only region. G-factor and SNR decreases in lower imaging area of PI with A-P acceleration, particularly 32ch coil shows steeper decrease from around 180mm in H-F direction (**Fig. 13A**). Both coils show SNR drop as much as 70%, ~55% and 43% - 40% at AF 2, 3 and 4, respectively (3rd column panels in **Fig. 13A**). In PI with acceleration in H-F direction, signal drop is 70%, 50% and 20% – 23% at AF 2, 3, and 4, respectively (**Fig. 13B**, 3rd column panels). Therefore, maximal AF in H-F (slice selection) and A-P (phase encoding) direction is 3 and 3 (or 4), respectively at the criteria of 50% (or ~42%) SNR decrease due to PI subsampling.

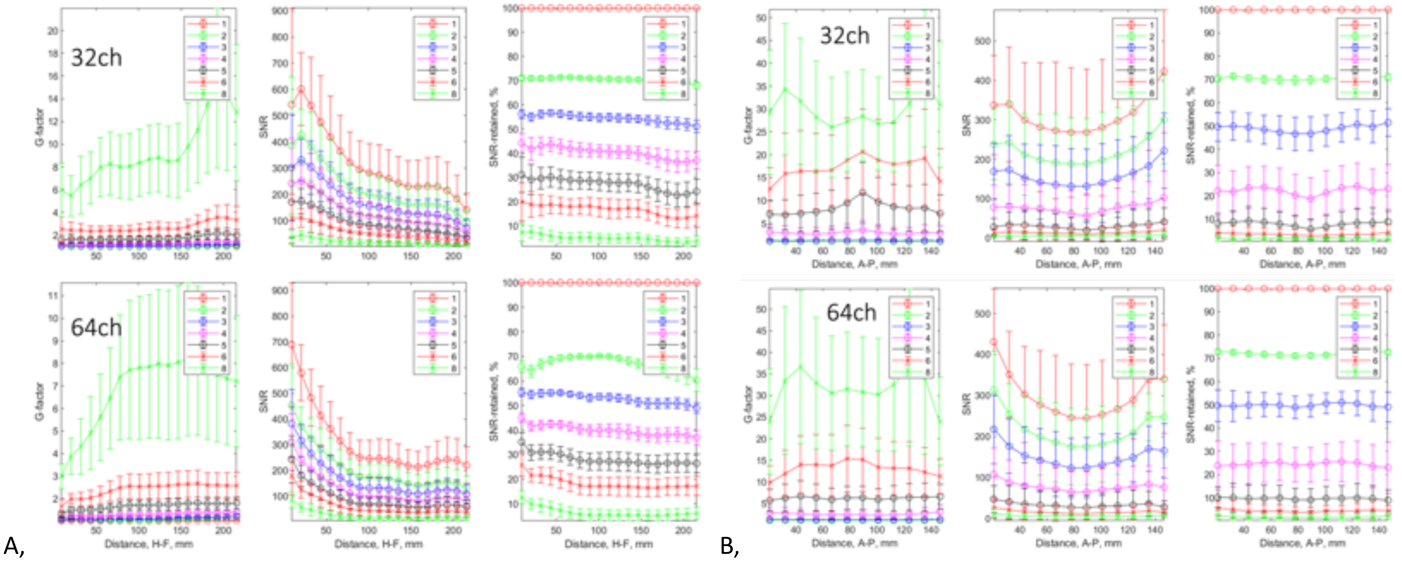


**Fig. 13** Measured PI g-factor, SNR, and SNR-retained for acceleration in **A**, Phase encoding (A-P) in transverse imaging; and **B**, slice selection (H-F) in sagittal imaging. AF 1, 2, 3, 4, 5, 6, and 8 are applied (different colored plots). X-axis represents different slice position, H-F slice and L-R slice in **A** and **B**, respectively.

PI performance indices are further plotted for AF 2 to 4 (**Fig. 14**). 64ch coil shows slightly higher SNR-retained at AF 4 for PI acceleration in H-F, slice selection direction, 21% vs. 23% (**Fig. 14A**). However, 64ch coil doesn't have advantage in A-P acceleration compared to 32ch coil, except more homogeneity in lower H-F imaging region (**Fig. 14B**).

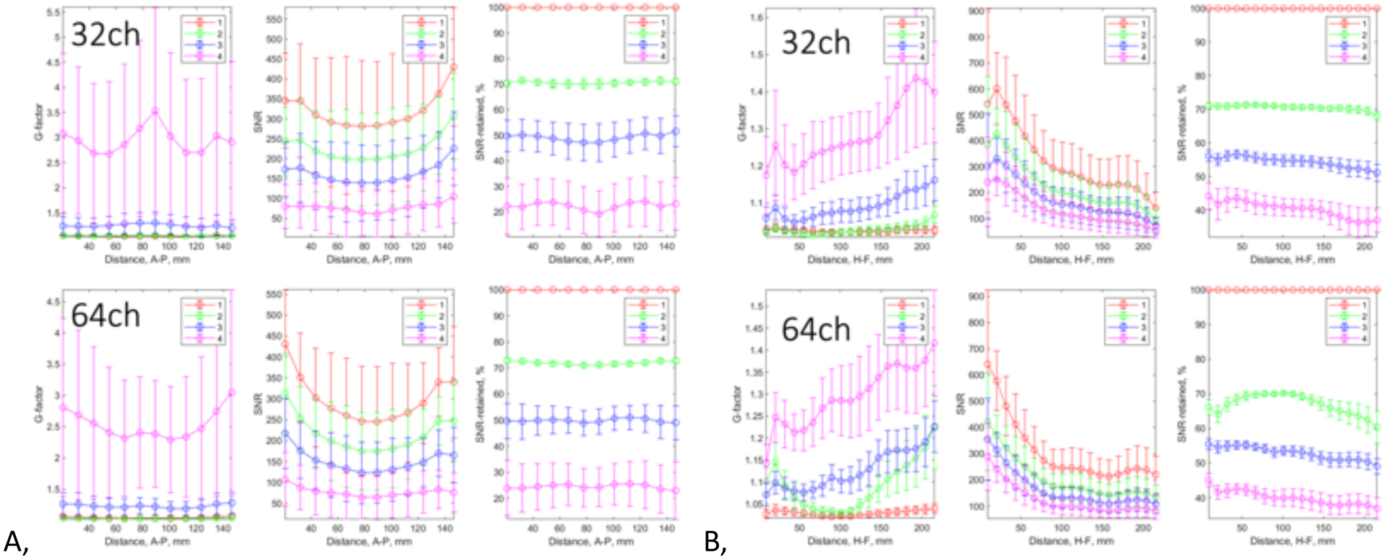
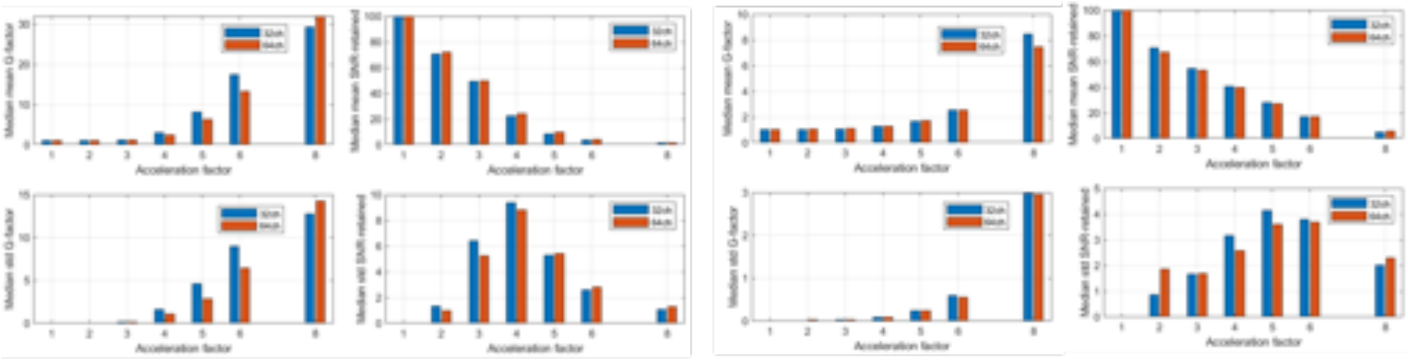


**Fig. 14** Measured PI performance of g-factor, SNR, and SNR-retained for acceleration in slice selection (H-F) in sagittal imaging (**A**) and phase encoding (A-P) in transversal imaging (**B**). AF is 1, 2, 3, and 4 in red, green, blue and magenta color.

Median values of PI performance indices (mean & std) are measured across the imaging slices – that is, L-R slices in sagittal imaging (H-F acceleration) and H-F slices in transversal imaging (A-P acceleration) (**Fig. 15**). PI performance of 64ch coil, i.e., g-factor and SNR-retained is a little superior to those of 32ch coil in slice selection (H-F acceleration) (**Fig. 15A**, top panels), while both coils have similar PI performance in phase encoding (A-P acceleration) (**Fig. 15B**, top panels), although 64ch coil produces more homogeneous SNR (**Fig. 15B**, bottom-right panel). 64ch coil shows less variant g-factor and SNR across different slices, particularly by AF 4 in PI in slice selection (**Fig. 15A**, bottom panels), which means 64ch coil produces less aliasing artifacts. It should be noted that PI in A-P phase encoding direction produces much higher SNR compared to PI in H-F slice direction, ~40% vs. ~20% at AF 4. This means higher AF could be applied in A-P than H-F direction.



A, Slice selection PI

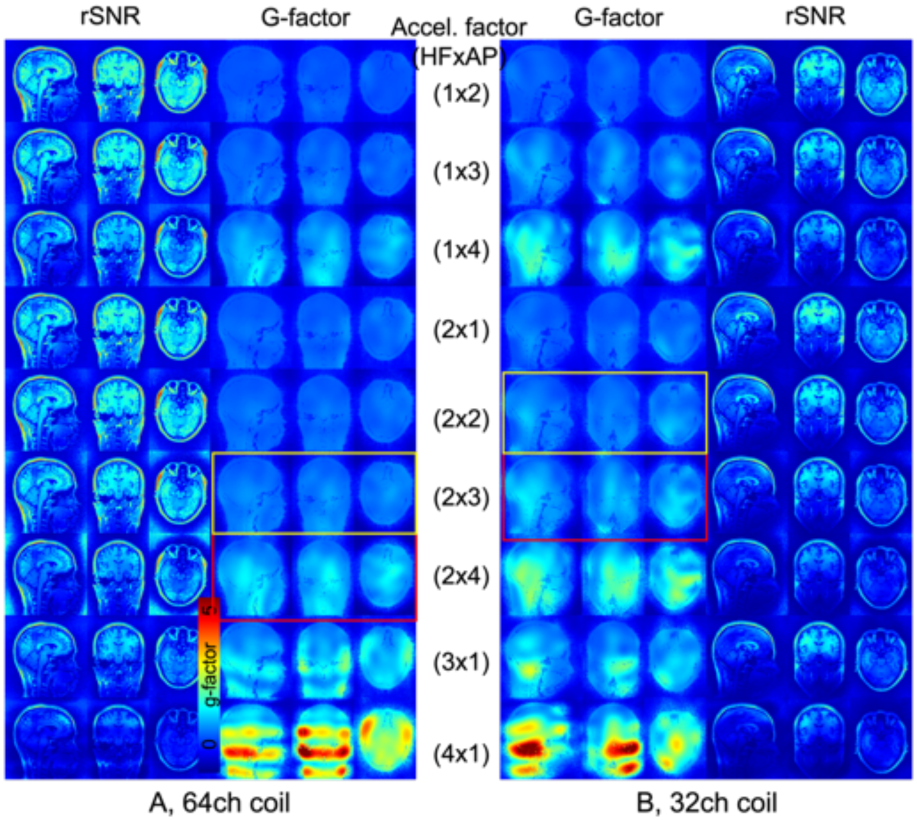
B, Phase encoding PI

**Fig. 15** Statistics comparison of 32ch vs 64ch coil in PI for slice selection (H-F) and phase encoding direction (A-P). Mean and std calculated in the image of transversal and sagittal slice. Median calculated over different slice, L-R in sagittal image and H-F in transversal image.

1D GRAPPA experiments with human head data are added in Supplementary materials. The trends are similar to those in phantom study.

## 2D GRAPPA

To investigate combined noise effect in simultaneous two-dimensional AF, 2D GRAPPA experiments were performed using full-sampled 3D MPRAGE k-space data of a subject head (**Fig. 16**). The results are not exactly same as those in 1D GRAPPA due to different GRAPPA kernel window, i.e., the dimension and the size. In 2D GRAPPA, 64ch coil shows a little better performance than 32ch coil. G-factor map shows AFs 2x2 and 2x3 (H-F[slice selection] x A-P[phase encoding]) is acceptable for 32ch and 64ch coil, respectively (yellow rectangles). With AFs 2x3 and 2x4 for 32ch and 64ch coil, the g-factor increases a little with inhomogeneity, but it seems still acceptable (red rectangles). 2D GRAPPA results show that AFs greater than 3 in H-F direction should be avoided for both 32ch and 64ch coil.



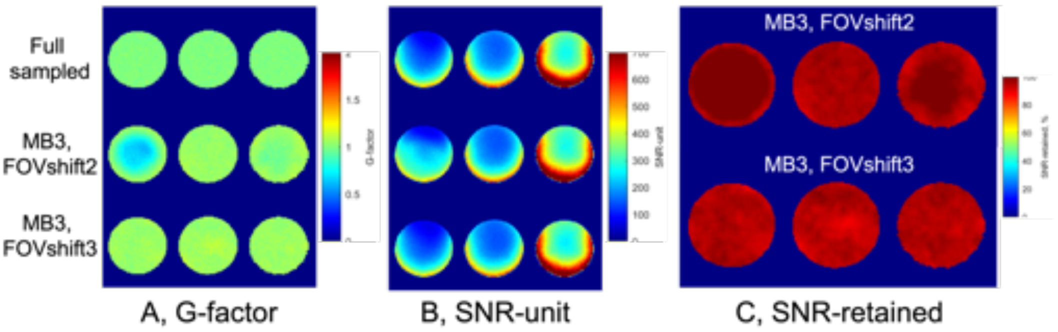
A, 64ch coil
B, 32ch coil

**Fig. 16** 2D GRAPPA simulation for different 2D acceleration factor in H-F and A-P direction with 64ch (**A**) and 32ch coil (**B**).

## SMS slice-GRAPPA

The performances, g-factor, SNR-unit and SNR-retained were measured using Siemens cylindrical phantom data acquired by 32ch and 64ch coil, separately. It is noted that SMS MB acquisitions usually maintain overall high SNR level by virtue of multiple slice excitation, that is, summation effect, which is not case for in-plane GRAPPA where subsampling results in SNR drop. In SMS MB slice-GRAPPA, there are three acceleration-related parameters – MB, FOV shift, and iPAT, if in-plane GRAPPA is applied.

**Fig. 17** shows the comparison of slice-GRAPPA for MB 3 with FOV shift 2 vs. 3 for 32ch coil. Siemens product SMS EPI w/ MB 3 and FOV shift 2, and CMRR SMS EPI w/ MB 3 and FOV shift 3. It shows FOV shift 3 has better image quality than that with FOV shift 2 at MB 3.



A, G-factor
B, SNR-unit
C, SNR-retained

**Fig. 17** Comparison of slice-GRAPPA for MB3 and FOV shift 2 (Siemens) vs. 3 (CMRR). **A**, G-factor map. **B**, SNR-unit map. **C**, SNR-retained map. Note that MB 3 with FOV shift 3 makes better quality of slice-GRAPPA reconstructed image. G-factor value is supposed to be greater than 1 but less than 1 (light blue color in **A**) is found due to GRAPPA regularization.

**Fig. 18** summarizes the results of slice-GRAPPA simulation for various AFs using 32ch coil – the applied MB and FOV shift are adopted from default parameters of Siemens and CMRR SMS MB EPI sequence; 2/2[1x2], 3/3[1x3], 4/3[1.3x3], 5/3[1.7x3], 6/3[2x3], 8/3[2.7x3], and 8/4[2x4] (MB/FOV shift [converted H-F AF/A-P AF in 2D GRAPPA]); it should be noted that CAIPI is applied, if FOV shift > 1. Overall SNR can be maintained as much as ~80% peak up to MB 8, however, spatial distribution of SNR becomes heterogenous with increase of MB factor, particularly >=MB ~6 (**Fig. 18C**). G-factor histogram shows FWHM of slice-GRAPPA with >=MB 6 becomes wider than 2 times compared to that of full-sampled image data (5th row panel in **Fig. 18B**). The wider g-factor brings SNR decrease as well as inhomogeneity caused by in aliasing artifact (**Fig. 18A** & **D**). Therefore, MB <= 5 is maximally allowed for 32ch coil, but >= MB 6 is not recommended for SMS MB EPI. The result is similar to that in 2D GRAPPA.

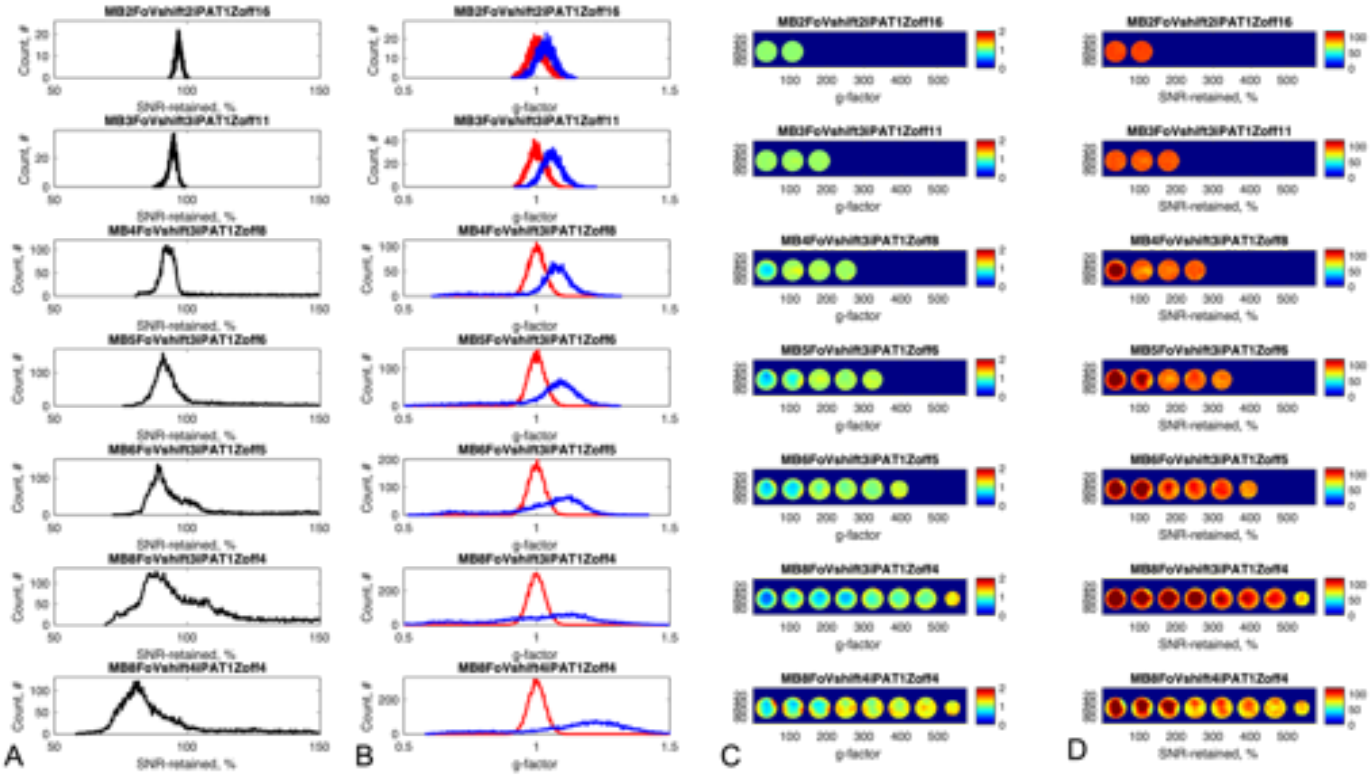


**Fig. 18** SMS MB slice-GRAPPA simulation for different MB and FOV shift for 32ch coil. **A**, Histogram of SNR-retained map. **B**, Histogram of g-factor map (red – full sampled data, blue – SMS MB data). **C**, G-factor map. **D**, SNR-retained map. Note that std of g-factor histogram increases with larger MB factor, that is, SNR decrease and aliasing.

SMS MB PI GRAPPA results with 64ch coil (**Fig. 19**) show very similar to those with 32h coil. SNR of 32ch coil looks tiny higher than 64ch coil, but the distribution is mostly overlapped with the histogram of 64ch data. Small difference of peak in g-factor and SNR-retained maps between 32ch vs. 64ch coil is possibly attributed to different number of channels but same number of noise simulation repetitions of 500 were applied for pseudo-replica simulation (see **Fig. 2** in [3]); 2x noise reduction requires 4x simulation repetitions. Regardless, the histogram of 64ch data is narrower and more homogeneous in slice direction than 32ch coil, which means less aliasing artifact (see MB4FOVshift3 and MB5FOVshift3). MB 6 looks maximally allowed for 64ch coil when combined with 1D GRAPPA results – MB 8 is not recommended for SMS MB EPI for 64ch coil because of too high heterogeneity in its distribution. It is noted that 64ch coil PI performance is superior to 32ch coil, particularly at high AFs.

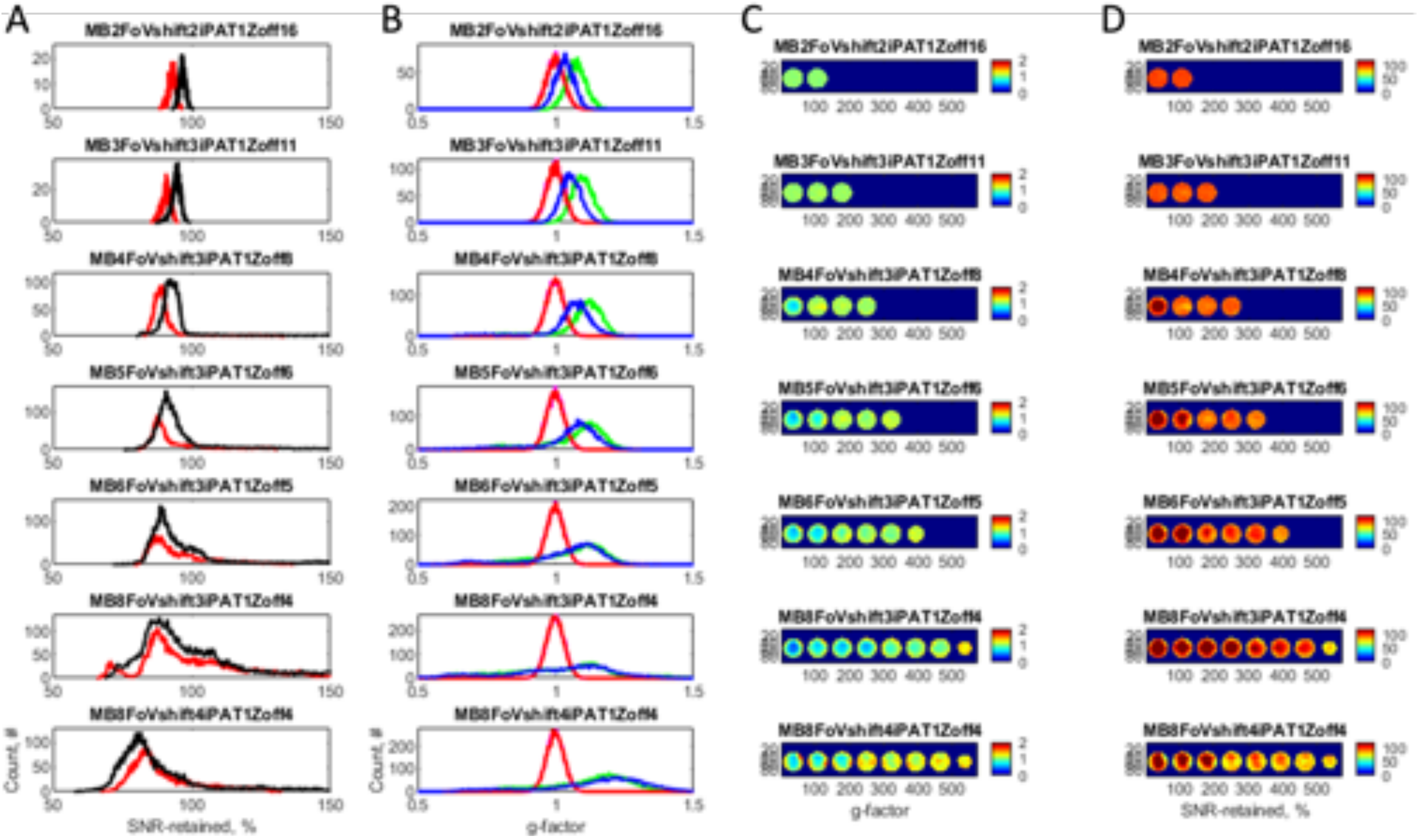


**Fig. 19** SMS MB slice-GRAPPA simulation for different MB and FOV shift for 64ch coil (red and green plots); 32ch SNR-retained and g-factor plotted together (black and blue plots). **A**, Histogram of SNR-retained map. **B**, Histogram of g-factor map (red – full sampled data, green – SMS MB data). **C**, G-factor map. **D**, SNR-retained map. Note that std of g-factor histogram increases with larger MB factor, that is, SNR decrease and aliasing.

With reconstructed SMB MB image, it is not easy to identify the noise. For example, SMS MB slice-GRAPPA image of a phantom with MB 8 and FOV shift 3 shows similar image quality (**Fig. 19A**), but g-factor and SNR map shows high spatial inhomogeneity in plane and across slice (see **Figs. 19B-D**). So, it is warranted the careful attention is required for high MB SMS image in noise quality assurance.

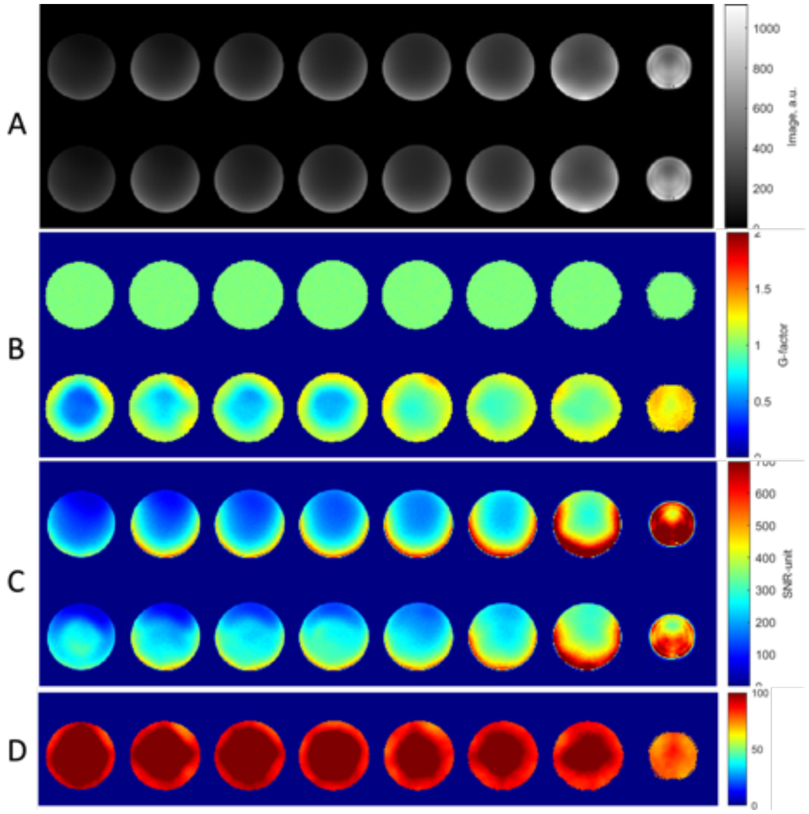


**Fig. 19** SMS MB slice-GRAPPA images for MB 8 and FOV shift 3. **A**, Reconstructed image intensity. **B**, G-factor map. **C**, SNR-unit map. **D**, SNR-retained map. Upper panel images are full-sampled data as reference and lower panel images are SMS MB data in **A**, **B**, and **C**. Image slice order is from low to high position from left and right.

**Fig. 21** shows the results of slice-GRAPPA & GRAPPA of SMS MB data for different MB, FOV shift and iPAT factor. 32ch coil produces good quality of MB image up to MB 3 with FOV shift 3 and iPAT 2 (3rd row in **Fig. 21**). The image maintains ~65% SNR and has good homogeneous SNR profile. However, MB 4 with FOV shift 3 and iPAT 2 (5th red-boxed row in **Fig. 21**) decreases SNR by ~50% as well as spatial homogeneity poor. MB >= 5 and iPAT 2 acceleration shows further SNR loss and inhomogeneity increase. Therefore, for 32ch coil, MB 4 and iPAT 2 could be the margin for acceptable SMS MB EPI image.

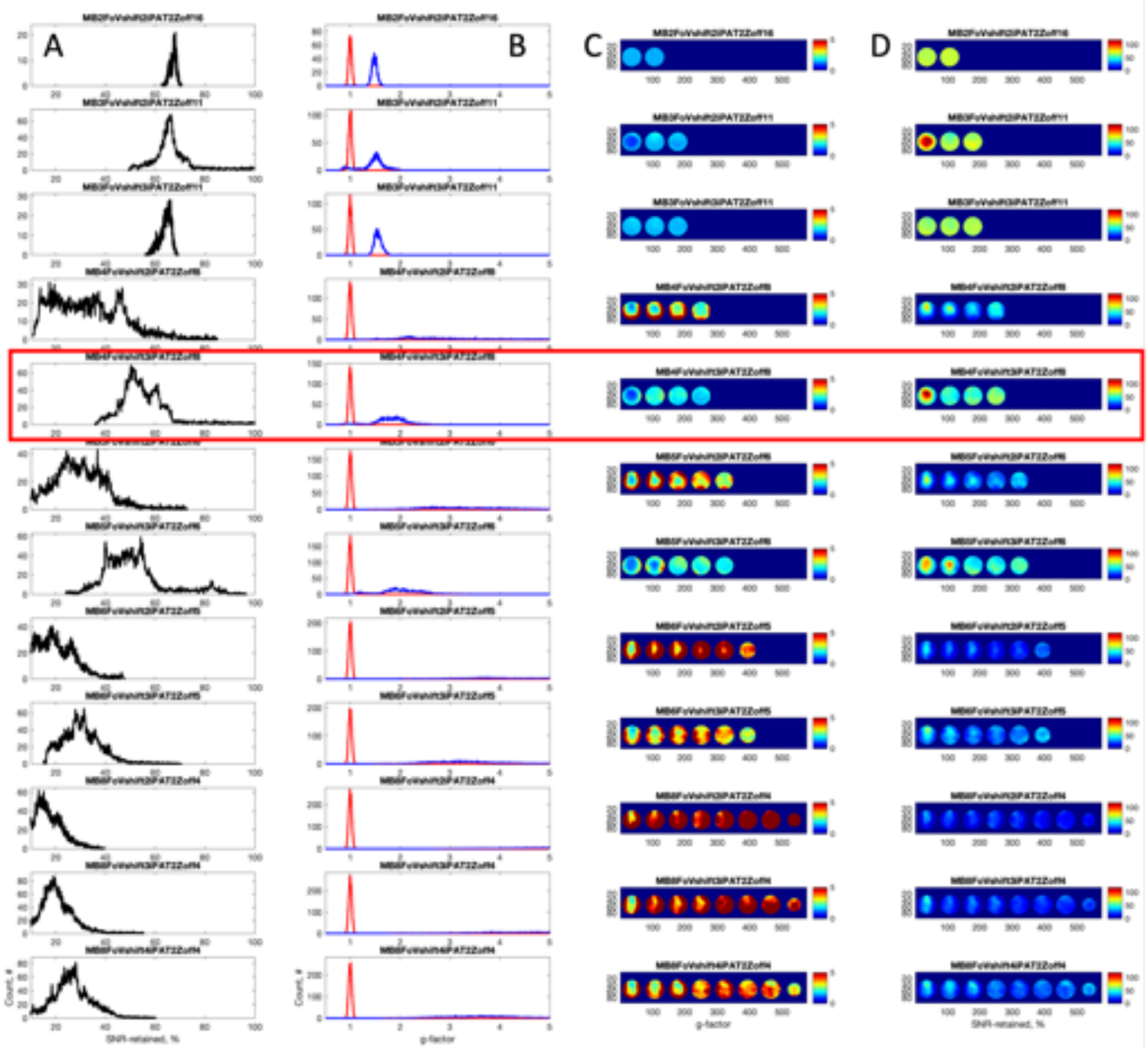


**Fig. 21** SMS MB slice-GRAPPA simulation for different MB and iPAT for 32ch coil. Note that FOV shift 3 makes better imaging quality than 2 for all MB 3, 4, 5, 6, and 8. **A**, Histogram of SNR-retained. **B**, Histogram of g-factor; red – full sampled and blue – SMS MB data. **C**, g-factor map. **D**, SNR-retained map. It should be noted that SMS MB with FOV shift is CAIPI encoding which improves the reconstructed image quality compared to orthogonal encoding such as in 2D GRAPPA.

In SMS MB and in-plane GRAPPA with 64ch coil, g-factor and SNR map shows a little better performance with more homogeneity than 32ch coil (**Fig. 22**). For 64ch coil, MB 5 and iPAT 2 could be the margin for acceptable SMS MB EPI image at criteria of 50% SNR loss (red rectangle). Interestingly, at MB 6 and iPAT 2 there is 40% SNR maintained while with relatively good homogeneity (cyan rectangle).

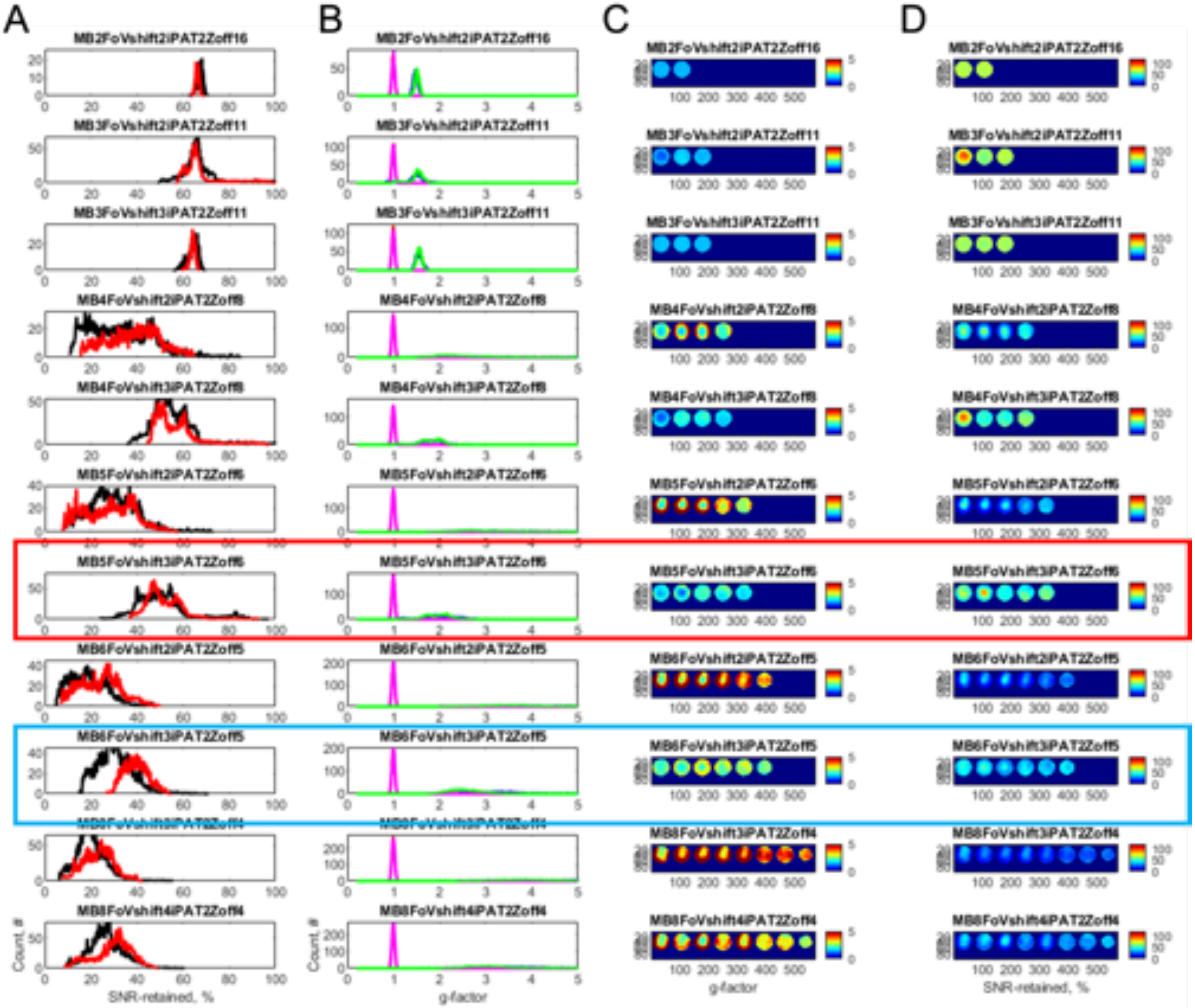


**Fig. 22** SMS MB slice-GRAPPA simulation for different MB and iPAT for 64ch coil (red and green plots); 32ch SNR-retained and g-factor plotted together (black and blue plots). **A**, Histogram of SNR-retained. **B**, Histogram of g-factor; red – full sampled and blue – SMS MB data. **C**, g-factor map. **D**, SNR-retained map. SMS MB EPI with MB 6 and iPAT 2 could be explored at expense of 40% SNR, if compensatory acquisition factor exists.

## DISCUSSION

Image SNR and GRAPPA PI performance of Siemens 32ch and 64ch coils at 3T Prisma scanner are investigated with a phantom and a human subject. Based on 1D GRAPPA, i.e., only one directional acceleration, reasonable acceleration factor in H-F (slice selection) or A-P direction (phase encoding in SMS MB EPI sequence) is <3 and <=3 at criteria of ~50% SNR reduction and/or 2x inhomogeneity increase by PI, respectively (**Table 5**). It is noted that PI SNR in slice direction (i.e., SMS MB acceleration) decreases much faster than that in phase encoding (i.e., in-plane GRAPPA acceleration, iPAT) at AF 4, for both 32ch and 64ch coil, ~23% vs. ~40%. If the criteria of 40% SNR reduction is applied, AF 3 and 4 could be acceptable H-F and A-P direction for 32ch and 64ch coil, if only average SNR is considered but not inhomogeneity. It should be noted that 64ch coil produces more homogeneous distribution of PI SNR in slice direction, that is, SMS MB acceleration direction (**Figs. 9** and **15**).

**Table 5.** SNR-retained for 1D GRAPPA simulation experiment by using Siemens cylindrical phantom.

| | **MB factor (median mean/std, %)** | | | **GRAPPA iPAT (median mean/std, %)** | | |
|---|---|---|---|---|---|---|
| **Coil** | 2 | 3 | 4 | 2 | 3 | 4 |
| 32ch coil | 70.5/1.3 | 49.5/6.4 | 22.4/9.4 | 70.7/0.9 | 54.7/1.7 | 40.7/3.2 |
| 64ch coil | 71.9/1.0 | 49.8/5.2 | 24.3/8.8 | 67.1/1.9 | 53.2/1.7 | 39.8 /2.6 |

Note: 'mean' and 'std' calculated from ROI, and 'median' of mean/std over imaging slice, i.e., sagittal and transversal slices for MB and iPAT simulation. Red colored AFs are allowed in 1D GRAPPA.

There are two popular SMS MB EPI sequences in Siemens Prisma 3T scanner for fMRI and DWI study – Siemens and CMRR SMS MB EPI sequence. For two representative EPI sequences, MB and iPAT parameters are adjustable by the user, but FOV shift is hidden and fixed in the sequence. FOV shift roles as the slice encoding in k-space of SMS MB EPI. For example, FOV shift 2 for MB 2 means that simultaneously-selected-two-slices are fully encoded in slice direction, i.e., by 2 encoding steps while the echo train are phase encoded with time. As a result, SMS EPI scan with MB 2 and FOV shift 2 acquires the image data with 2x subsampling in phase encoding direction but full sampling in slice selection; it is similar to 1x2 (H-F x A-P) in 2D GRAPPA. So, three AF parameters, MB, FOV shift and iPAT are important to estimate g-factor or SNR in SMS MB EPI sequence. The combination of three SMS MB PI parameters is listed in **Table 6**. The parameters between two representative sequences looks like same except MB 3; Siemens has FOV shift 2 but CMRR's FOV shift 3; slice-GRAPPA simulation showed FOV shift 3 image is better than 2 at MB 3. MB 3 is typically applied for DWI sequence, so SNR and homogeneity of CMRR SMS MB DWI is expected to be better than Siemens SMS MB DWI image.

**Table 6.** Default PI AF of MB, FOV shift (i.e., slice encoding in SMS), GRAPPA iPAT in Siemens and CMRR SMS MB EPI sequence.

| **Default PI parameters in Siemens SMS MB EPI** | | | | **Converted AFs to 2D GRAPPA[¶]** | |
|---|---|---|---|---|---|
| MB factor | FOV shift or PE[*] | iPAT | ACS reference lines | Slice selection, H-F | Phase encoding, A-P |
| 2 | 2 | 1 | x | 1 | 2 |
| 3 | 2 | 1 | x | 1.5 | 2 |
| 4 | 3 | 1 | x | 1.33 | 3 |
| **5** | **3** | **1** | **x** | **1.67** | **3** |
| **6** | **3** | **1** | **x** | **2** | **3** |
| 8 | 3 | 1 | x | 2.67 | 3 |
| 2 | 2[?] | 2 | 24 | 1 | 4 |
| 3 | 2[?] | 2 | 24 | 1.5 | 4 |
| **4[§]** | **2[?]** | **2** | **24** | **2** | **4** |
| **5** | **2[?]** | **2** | **24** | **2.5** | **4** |
| 6 | 2[?] | 2 | 24 | 3 | 4 |
| 8 | 2[?] | 2 | 24 | 4 | 4 |
| **Default PI parameters in CMRR SMS MB EPI** | | | | **Converted AFs to 2D GRAPPA** | |
| 2 | 2 | 1 | x | 1 | 2 |
| 3 | 3 | 1 | x | 1 | 3 |
| 4 | 3 | 1 | x | 1.33 | 3 |
| **5** | **3** | **1** | **x** | **1.67** | **3** |

| | | | | | |
|---|---|---|---|---|---|
| **6** | **3** | **1** | **x** | **2** | **3** |
| 8 | 3 | 1 | x | 2.67 | 3 |
| 2 | 4[?] | 2 | 24 | 1 | 4 |
| 3 | 4[?] | 2 | 24 | 1.5 | 4 |
| **4[§]** | **4[?]** | **2** | **24** | **2** | **4** |
| **5** | **4[?]** | **2** | **24** | **2.5** | **4** |
| 6 | 4[?] | 2 | 24 | 3 | 4 |
| 8 | 4[?] | 2 | 24 | 4 | 4 |

[*] PE in CMRR EP seems to be multiplication of FOV shift and iPAT. For example, PE 4 at iPAT 2 is FOV shift 2 and iPAT 2.

[§] For SMS MB EPI sequence, AFs, MB 4 and iPAT 2 are recommended for 64ch coil, but not 32ch coil.

[¶] No CAIPI encoding is applied in 2D GRAPPA but applied in SMS MB EPI if FOV shift is greater than 1.

* Blue and red parameters are marginally acceptable for 32ch and 64ch coil, respectively.

[?] FOV shift is hidden in SMS EPI sequence, the values in the table are assumed to be optimal.

In SMS MB EPI sequence, two AFs, i.e., in slice selection and phase encoding are applied and the image is reconstructed by two GRAPPA, that is, slice-GRAPPA and in-plane GRAPPA. Maximal AF found from 1D GRAPPA experiment, that is, exclusive application of each directional AF could be a reference for higher-than maximal AF parameters in 2D GRAPPA. Therefore, it is practical to estimate maximum AFs found from 2D GRAPPA experiments, if for SMS MB EPI acquisition. With AFs of 2 x 2 and 2 x 3 (slice selection[H-F] x phase encoding[A-P]) is ideal for 32ch and 64ch coil, respectively. With AFs of 2 x 3 (H-F x A-P) for 32ch coil, g-factor increases a little and inhomogeneity increase; similarly, as in SMS MB EPI, MB 6 and FOV shift 3 becomes heterogeneous for 32ch coil, although peak SNR is maintained as much as 87% by CAIPI encoding. Accordingly, in Siemens and CMRR SMS MB EPI sequence, maximal MB 5 with FOV shift 3 in SMS MB EPI (i.e., AF <2 x 3 [H-F x A-P] in 2D GRAPPA) is recommended for 32ch coil. In 64ch coil, SNR homogeneity in SMS MB EPI is improved at >=MB 6 with FOV shift 3 or 4 compared to 32ch coil, implying that 64ch coil PI is slightly better than 32ch coil for such a high AF PI. So, MB 6 with FOV shift 3 is marginally acceptable for 64ch coil. MB 8 and FOV shift 3 or 4 is not acceptable due to large inhomogeneity for both 32ch and 64ch coil, although peak SNR ~80% – ~85%.

When in-plane acceleration is required together with MB acceleration as in SMS MB multiple TE (or multi-echo, ME) EPI sequence, MB 3 with FOV shift 3 and iPAT 2 is ideal with 65% SNR and good homogeneity for both 32ch and 64ch coil. However, when further acceleration is needed for faster or more echo acquisition, maximal MB 4 and iPAT 2 (i.e., converted AF ~2 x ~4 [H-F x A-P] in 2D GRAPPA) could be recommended for 32ch coil at expense of ~50% SNR loss and with increased inhomogeneity. It should be noted the maximum AFs could be increased with CAIPI encoding applied in SMS MB sequence, particularly in phase encoding, A-P direction as its higher SNR, e.g., iPAT > 4. MB 5 and iPAT 2 is marginally acceptable for only 64ch coil, with SNR loss, >= ~50% and homogeneity improved compared to 32ch coil. If further aggressive acceleration is applied, MB 6 and iPAT 2 will result in 40% SNR – this exploring condition could be tried only with 64ch coil.

The limitation of the study is that PI GRAPPA performance was investigated only in spatial image or k-space domain, but not combined with temporal domain, for example, relationship between AF and temporal sampling rate in total SNR estimation. However, the induced SNR decrease by parallel imaging with MB or iPAT is projected on to total SNR, which means the reduced SNR can't be compensated by temporal parameters. There is no data provided for SNR change in time domain by fast MRI scan via PI in the study; other studies can be found [7]. On the other hand, SMS MB acquisition and slice-GRAPPA in this study could be different from those implemented in the scanner, but the general idea of the reconstruction algorithm should be similar. FOV shift is hidden in the sequence, it can't be modified in both EPI sequences. The parameter is believed to be optimally set at release of the sequences; however, it seems only done for low MB factor such as 3, particularly without in-plane GRAPPA. At the best estimation of this hidden parameter in both SMS EPI sequences, FOV shift is set as '2' for all different MB factors (see **Table 6**). In the study, it is assumed that default FOV shift is optimally set combined with PI reconstruction in the scanner in terms of SNR and unaliasing, so FOV shift 3 is considered instead of 2 in the simulation experiments.

## CONCLUSION

Parallel imaging in MRI acquisition reduces total scan time at expense of lower SNR. Faster scan is important in functional and diffusion tensor MRI to measure dynamics of physiology change or to reduce total scan time within acceptable range < ~15min. To acquire and reconstruct the accelerated PI data, it requires multiple channel receiver coil, therefore the imaging performance is determined mainly by the number of coil's channels and the geometry of the coil loops. In MRRC UPMC, Siemens 32ch and 64ch head(/neck) multi-channel receiver coils are available for Siemens Prisma 3T scanners. However, due to the intrinsic characteristics of PI acquisition, that is, the subsampling of k-space data, SNR reduction and/or aliasing is unavoidable. In the study, SNR decrease in PI acquisition is investigated under different PI acquisition and various acceleration parameters using in-plane GRAPPA and SMS slice-GRAPPA, therefrom maximal AFs based on criteria of 50% SNR are suggested for 32ch and 64ch multi-channel receiver coils. The recommended AFs could be referenced for functional and diffusion study requiring fast SMS MB EPI sequences.

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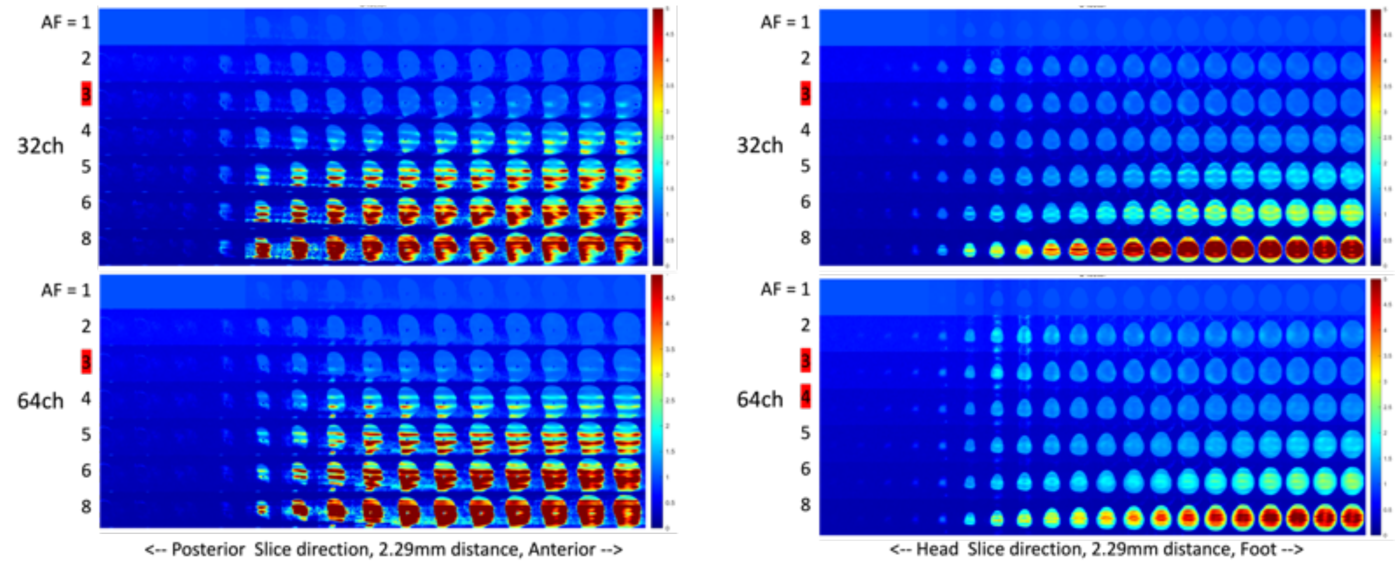
## SUPPLEMENTARY MATERIALS

### Parallel imaging of human subject head

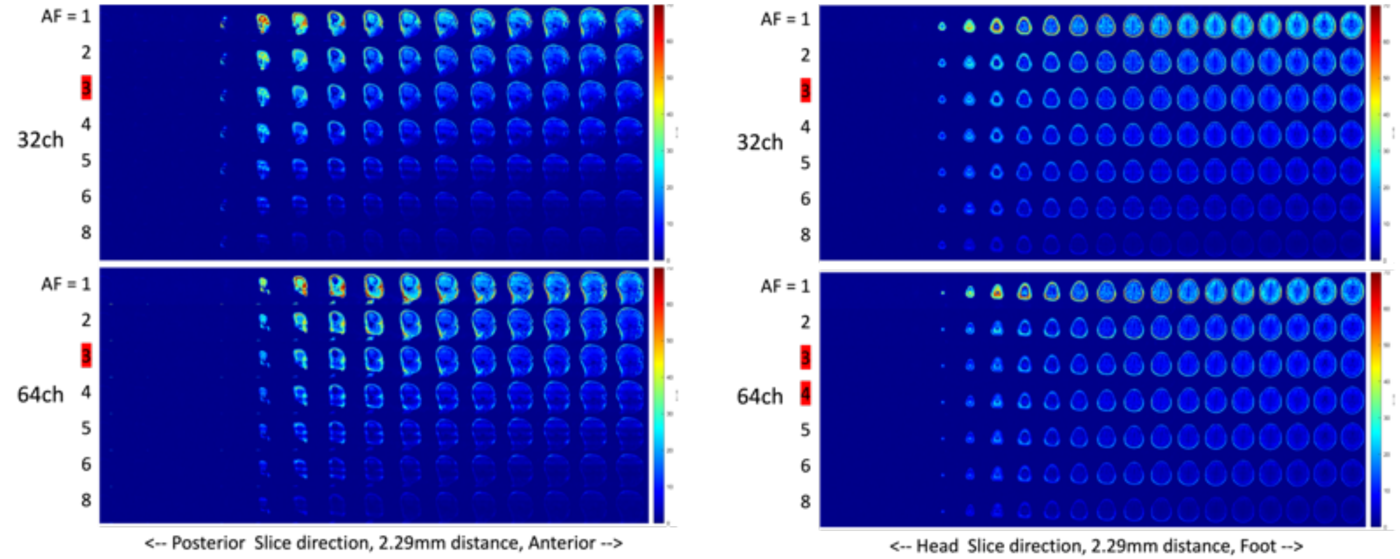
T1 MPRAGE sequence images are acquired using 32ch and 64ch coil in same session. The subject head is positioned in deep coil as much as position until the vertex touching the coil plastic frame – which will maximize the imaging SNR. GRAPPA PI simulation is performed same as in the phantom study; two acceleration/subsampling is in H-F and A-P direction, that is, slice selection and phase encoding in typical SMS MB EPI scan.

G-factor map in **sFig. 1** for H-F acceleration shows 64ch superior to 32ch coil. MB 2 and 3 produces low and relatively homogeneous g-factor values. In A-P acceleration, 64ch performance is slightly better than 32ch. AF in A-P seems acceptable marginally by iPAT 4. SNR in **sFig. 2** and **3** is retained with 60 – 70% and 50 – 60% for AF in H-F of 2 and 3, while <40% for greater than AF 4. SNR retained with >50% and >40% for AF in A-P of 3 and 4, respectively. GRAPPA image quality dramatically decreases with AF (**sFig. 4**).

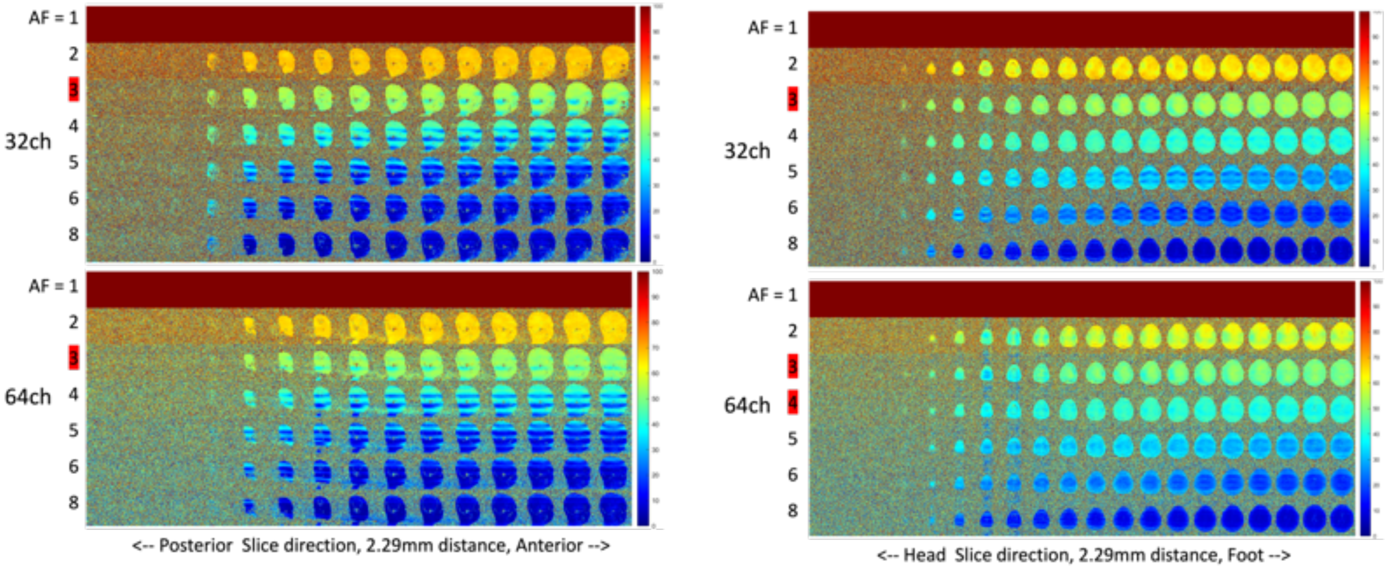
GRAPPA PI performance results are similar to those in the phantom study. The human head study shows slightly better in PI with A-P acceleration compared to the phantom, marginally acceptable AF 4 vs. 3.



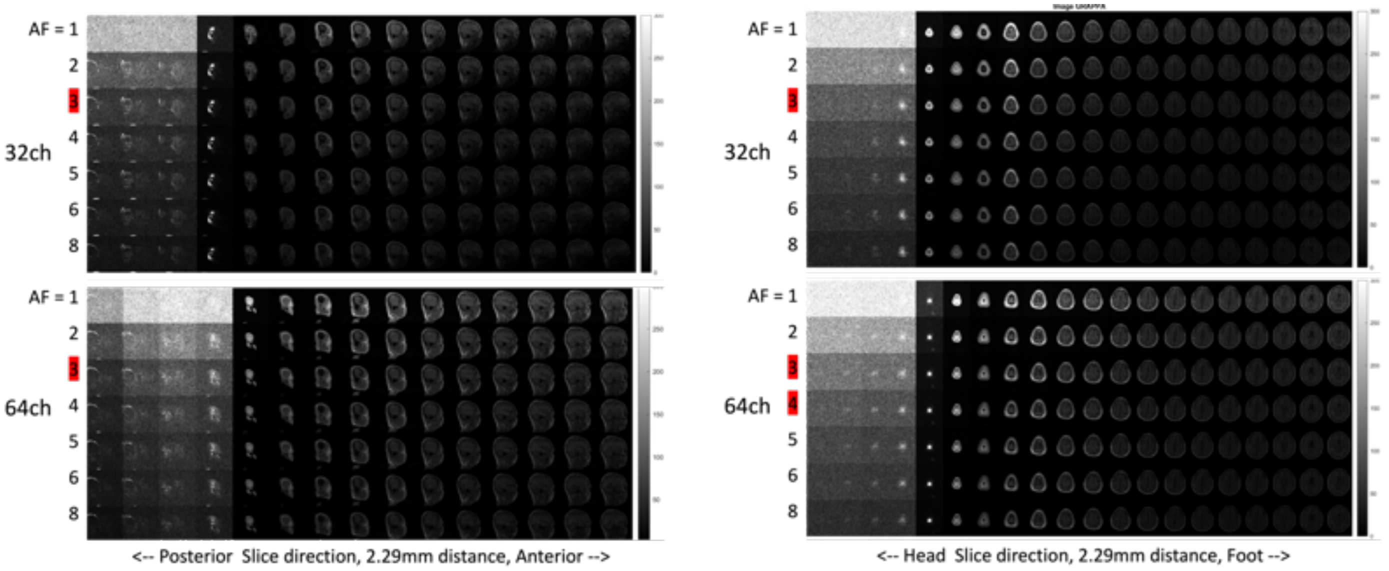
**sFig. 1** G-factor map. **A**, Acceleration direction in H-F, i.e., slice selection in SMS MB EPI. **B**, Acceleration in A-P, i.e., phase encoding in SMS MB EPI.



**sFig. 2** SNR unit map. **A**, Acceleration direction in H-F, i.e., slice selection in SMS MB EPI. **B**, Acceleration in A-P, i.e., phase encoding in SMS MB EPI.



**sFig. 3** SNR-retained map. **A**, Acceleration direction in H-F, i.e., slice selection in SMS MB EPI. **B**, Acceleration in A-P, i.e., phase encoding in SMS MB EPI.



**sFig. 4** GRAPPA image. **A**, Acceleration direction in H-F, i.e., slice selection in SMS MB EPI. **B**, Acceleration in A-P, i.e., phase encoding in SMS MB EPI.