

The SENSE Ghost: Field-of-View Restrictions for SENSE Imaging

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Purpose: To describe a known (but undocumented) limitation in parallel imaging using simulation and experiment. This limitation consists of an artifact that appears when the imaging field of view (FOV) is less than the object size. This study demonstrates this artifact in the phase- and partition-encoding dimensions.

Materials and Methods: One-dimensional simulations as well as in vivo experiments were performed with FOVs greater and less than the object being imaged. Full-FOV, reduced-FOV, and SENSE reconstructions were visually compared.

Results: Image artifacts occurred when the final SENSE FOV was smaller than the object being imaged. This artifact, termed the SENSE ghost, was a residual fold-over/aliasing artifact. Its location was in the central portion of the image rather than at the edges of the image.

Conclusion: This image artifact results from an FOV being smaller than the imaged object. The SENSE reconstruction cannot unfold this additional fold-over, and will place it in a predictable image location based on the SENSE reduction factor. Knowledge of this artifact is necessary when prescribing SENSE acquisitions and interpreting the resulting images.

Key Words: image reconstruction; image artifact; parallel imaging

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ALIASING is a well understood phenomenon that occurs whenever a signal is sampled with a sampling frequency that does not exceed by two times the band of frequencies that is contained in the signal. In MR imaging (MRI), aliasing of the signal occurs when the distance between k-space samples is less than one over the object size. Aliasing can be a source of artifacts in all three MRI directions (1). In conventional MRI, image domain aliasing artifacts occur when the imaging field

of view (FOV) is smaller than the imaged object. Common names for this artifact include aliasing, ghosting, fold-over, and wrap. This artifact can be removed by increasing the FOV through finer readout sampling or additional phase-encoding sampling. Also, band-pass filtering, an astute orientation of the phase-encoding direction, or sharper slice profiles in three-dimensional imaging may be employed.

A combined acquisition/reconstruction method, called subencoding (2), was one of the first proposals made to reduce MRI times using multiple detectors. This concept was recently refined in other techniques for applications to many existing protocols. One such technique is commonly referred to as sensitivity encoding (SENSE) imaging (3). SENSE imaging allows one to collect a reduced number of raw data phase-encoding lines without sacrificing image resolution or FOV. A subset of k-space data is collected that does not satisfy the Nyquist sampling rate, and conventionally results in images that have an artifactual periodic replication of the imaged object. Multiple receiver coils and a sophisticated reconstruction algorithm are used to unfold the conventional reduced-FOV image into a full-FOV image.

SENSE reconstruction relies on the solution of linear equations. The solution is governed by the coil sensitivities, imaging plane, and SENSE factor. In this study it is shown that in addition, the correct solution is also based on the SENSE full-FOV size in relation to the object size. As in conventional imaging, a restriction is placed on the FOV size in relation to the object size to obtain images without residual aliasing.

MATERIALS AND METHODS

The SENSE method has been described in detail elsewhere (3). To analytically demonstrate the source of SENSE artifacts, and show their relation to the object size and unfolded-FOV, I performed a simulation using a simple rectangular function with different sizes relative to the FOV. Qualitative examples of the SENSE ghost were obtained from volunteers to provide in vivo reference images for clinical scenarios.

Computer Simulations

One-dimensional simulations were performed with the use of a real valued rectangular object and two radio-

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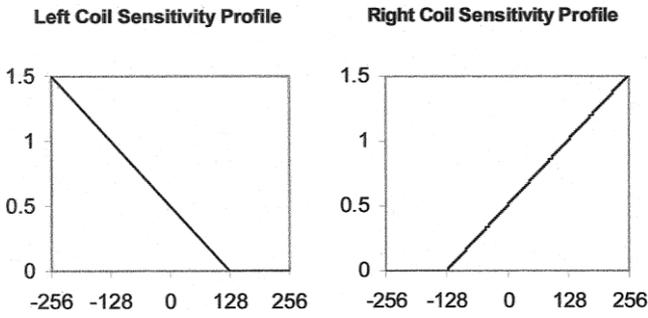


Figure 1. Right and left coil sensitivity profiles used for the simulations in Fig. 2 (x-axis units: mm; y-axis units: arbitrary units).

frequency (RF) coils (right and left) with simulated real valued linear sensitivity profiles (Fig. 1). A SENSE factor of 2 was used for all simulation cases. Three simulations were performed using a true object size of 100 mm (case 1), 200 mm (case 2), and 300 mm (case 3). Reconstructions were performed to generate reduced-FOV individual coil images (128 mm, right and left), a full-FOV (256 mm) sum-of-squares image (4), a reduced-FOV (128 mm) sum-of-squares image, and a SENSE reconstruction. All simulations were done with a 1-mm resolution. The results were evaluated for aliasing in full-FOV, reduced-FOV, and SENSE reconstructions.

In Vivo Experiments

Scanning was performed on a 1.5-T clinical scanner (Philips Gyroscan Intera, Best, The Netherlands). Two

healthy volunteers with no contraindications for MRI participated. The study protocol was approved by the institution’s human investigations committee, and written informed consent was obtained from the subject after the imaging procedure had been fully explained. A flexible wraparound cardiac coil with five elements was used. The longer diameters of the coil elements were aligned to the head-foot direction. A two-dimensional balanced fast-field-echo sequence (TR/TE = 2.6/1.3 msec, FA = 55°) was used. Sensitivity maps were calculated by dividing the individual coil images by the body coil image. SENSE images were acquired in the axial, short-axis, and horizontal long-axis orientations of the heart. Images in the same orientations were also acquired with a full set of phase-encoding steps. SENSE factors of 1.2, 1.5, and 2.0 were used. In some cases, images were purposely prescribed such that the reconstructed FOV was slightly smaller than the patient’s body size. Thus, two-dimensional in vivo reconstructions similar to the computer simulation cases were performed. Also, coronal three-dimensional balanced fast-field-echo acquisitions (TR/TE = 4.1/1.1 msec, FA = 20°) were used to image the abdomen with SENSE encoding (SENSE factor = 2) performed in the third dimension (anterior/posterior). Three-dimensional FOVs were prescribed such that they were greater and less than the subject’s size. All images were subsequently evaluated for artifacts.

RESULTS

The results of the computer simulations are given in Fig. 2. In case 1, where the object size was less than the

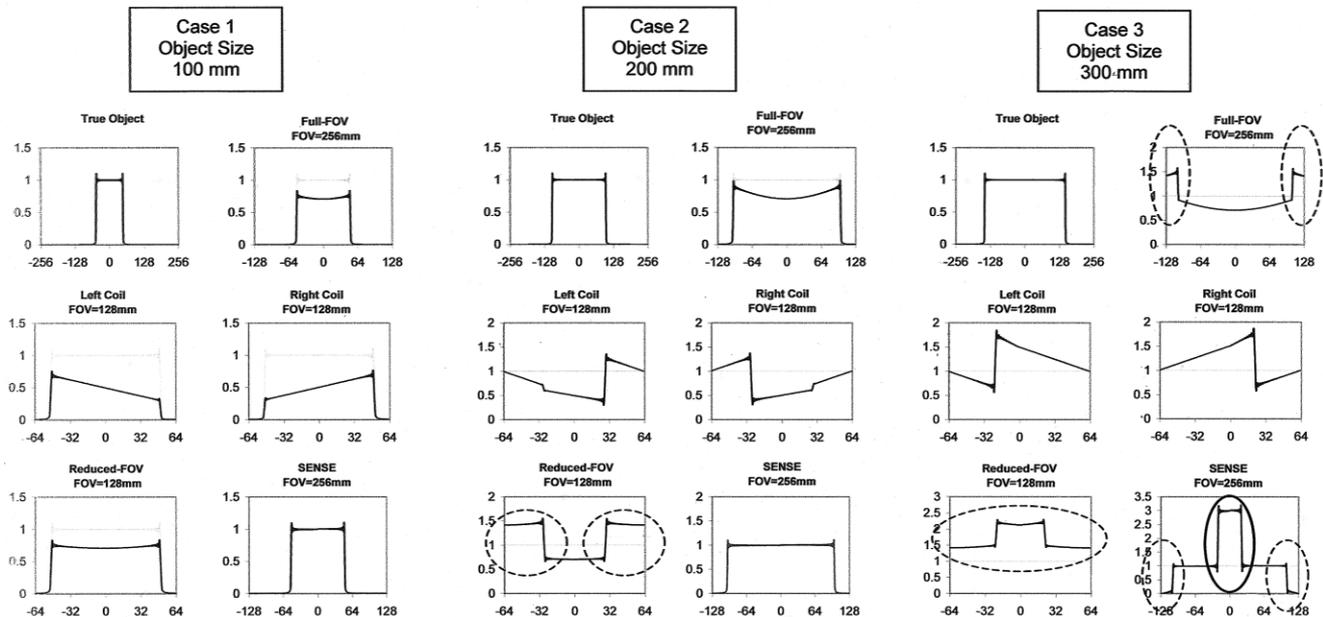


Figure 2. One-dimensional simulations demonstrating aliasing artifacts in conventional and SENSE imaging. In cases 1 and 2, SENSE provides an artifact-free reconstruction. In case 3, the SENSE reconstruction has artifacts in the center as well as the edges of the FOV. Circles mark the image artifacts. The solid circle marks the SENSE ghost. Each plot has the artifact-free reconstruction shown with a finer line. In some cases, the curves are identical or the FOV is not large enough to show the entire object, and a flat line is seen (x-axis units: mm; y-axis units: arbitrary units).

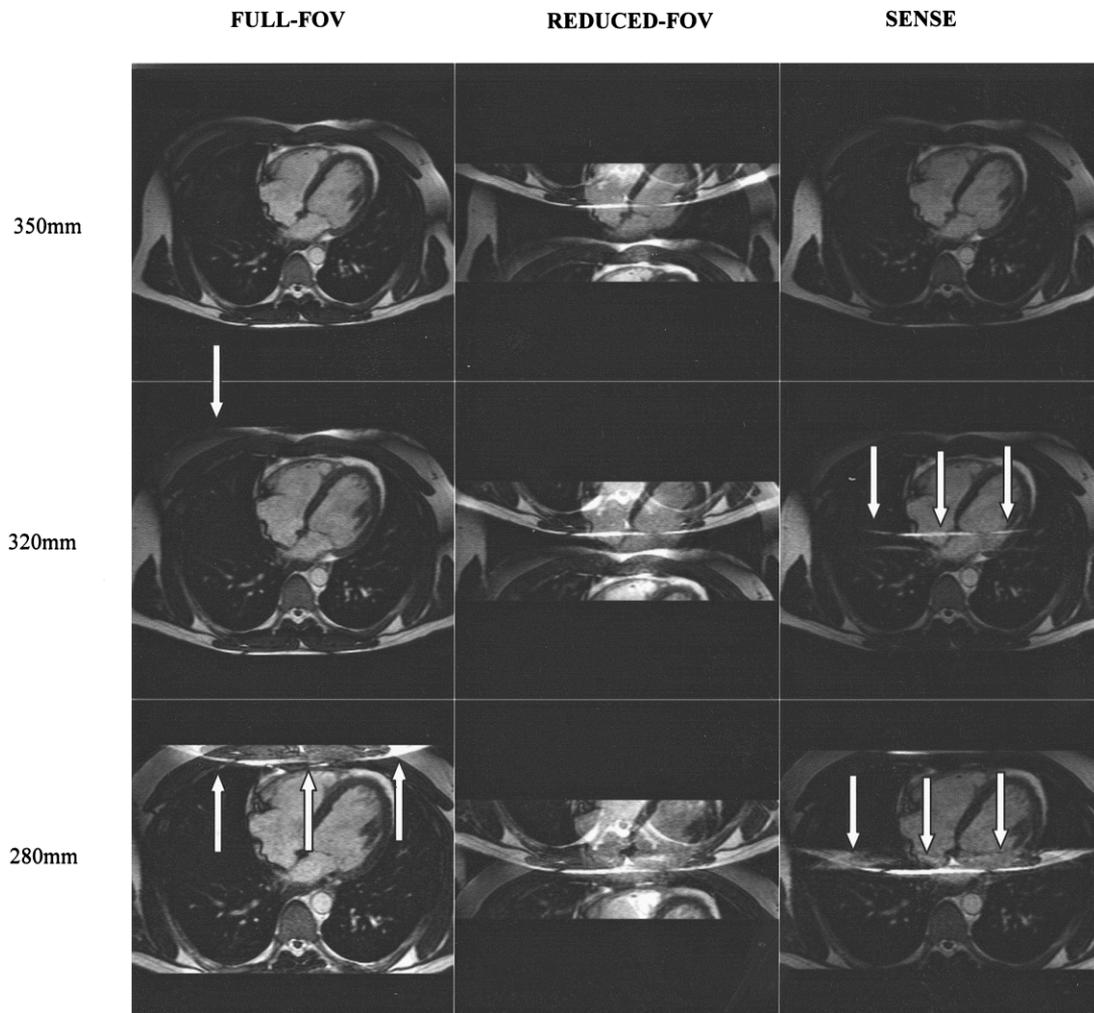


Figure 3. Axial images demonstrating the SENSE ghost and its relation to FOV; SENSE factor = 2. Top row: Artifact-free reconstruction; the reconstructed image FOV is larger than the object. Middle row: Minor artifact; the reconstructed image FOV is slightly smaller than the patient's body. Bottom row: Major artifact; the reconstructed image FOV is significantly smaller than the patient's body. Note: The aliasing is at the edge of the full-FOV images, and in the center of the SENSE images. Phase encoding and SENSE were performed in the vertical direction. Arrows show the location of aliasing in full-FOV and SENSE images.

reduced-FOV and the full-FOV, no artifacts occurred in the reduced-FOV or SENSE reconstruction. In case 2, where the object size was *greater* than the reduced-FOV but *less* than the full-FOV, artifacts were noted at the edge of the reduced-FOV, but the SENSE reconstruction was artifact-free. In case 3, where the object size was *greater* than the reduced-FOV *and* the full-FOV, artifacts were present throughout the reduced-FOV. In the SENSE reconstruction, artifacts were present at the edges and in the center (SENSE ghost).

Sum-of-squares reconstructions did not correct for the coil sensitivities. SENSE reconstructions did correct the nonuniform coil sensitivities, and provided an exact reconstruction when the object size was smaller than the reconstructed FOV (cases 1 and 2).

In the in vivo experiments (Figs. 3 and 4), artifacts were seen in the center of the SENSE acquisitions when there were fold-over artifacts in the conventional full-FOV acquisitions. In Fig. 4, phase encod-

ing was intentionally used in the right-left dimension. This may be an unconventional choice, but it was chosen to best depict the artifact and its source. A reduction in the SENSE factor (Fig. 5) moved the SENSE ghost in the reduced-FOV acquisitions toward the edges of the image, demonstrating that the position of the artifact was dependent on the SENSE factor. In Fig. 6, a pictorial method is presented to predict the spatial artifact location for several SENSE factors. The three-dimensional acquisitions (Fig. 7) showed artifacts similar to two-dimensional acquisitions after reslicing. Artifacts in the source images were not readily identifiable as resulting from the SENSE reconstruction.

In all acquisitions, images reconstructed with a full set of phase-encoding lines (full-FOV) had artifacts at the edges of the image. SENSE images had characteristic artifacts in the central portion of the image (SENSE ghost) as well as at the edges of the image.

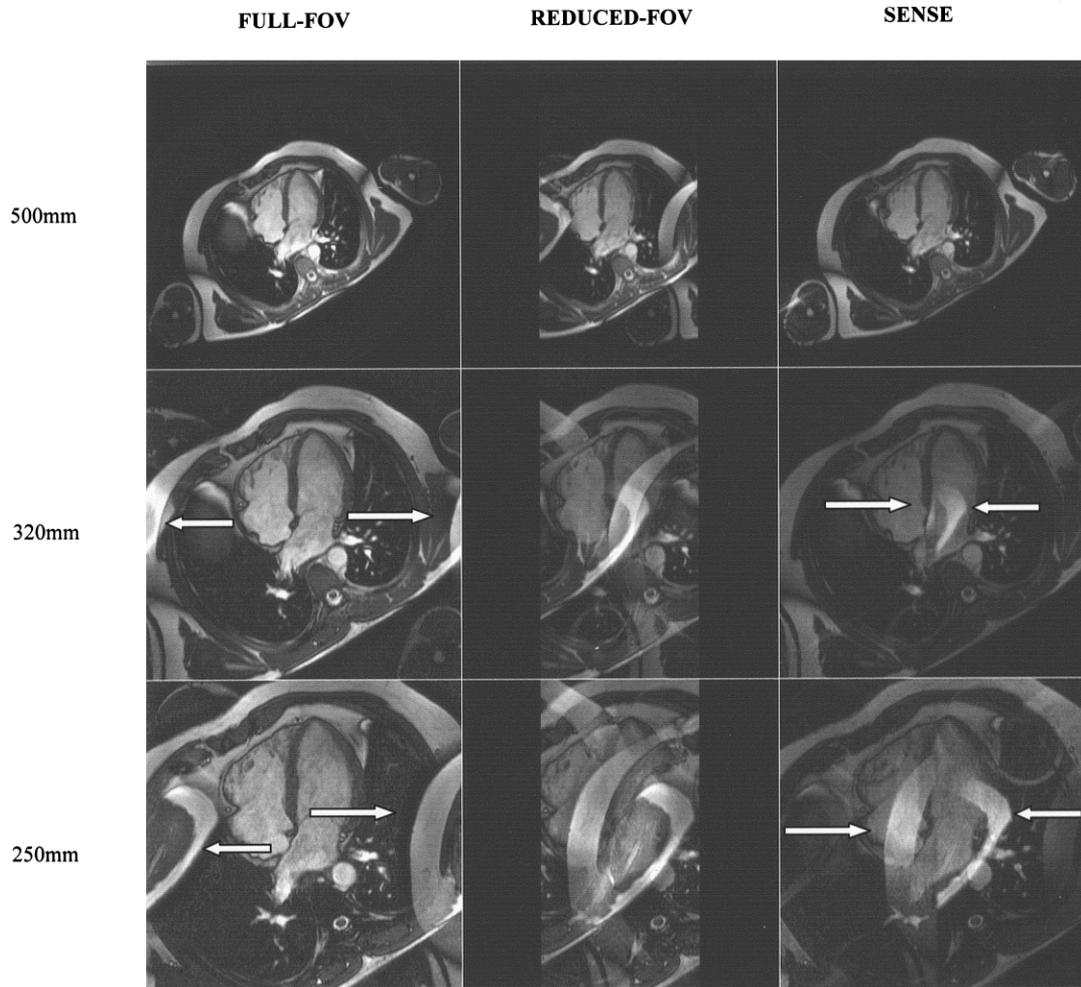


Figure 4. Horizontal long-axis images demonstrating the SENSE ghost and its relation to FOV; SENSE factor = 2. Top row: Artifact-free reconstruction; the reconstructed image FOV is larger than the object. Middle row: Small artifact; the reconstructed image FOV is slightly smaller than the patient's body. Bottom row: Major artifact; the reconstructed image FOV is significantly smaller than the patient's body. The aliasing is at the edge of the full-FOV images, and in the center of the SENSE images. Phase encoding and SENSE were performed in the horizontal direction. Arrows show the location of aliasing in full-FOV and SENSE images.

DISCUSSION

There are two motivations for understanding artifacts in a new imaging modality (1). First, it is important for the image interpreter to be aware of artifactual signals that can appear in the image in order to guard against making a false diagnosis. Second, it is important to identify and study artifacts to understand their origins and develop some means of eliminating them from diagnostic images.

An artifact particular to SENSE imaging has been described and demonstrated. The characteristic artifact occurs when the reconstructed FOV is smaller than the object being imaged. SENSE imaging does not possess the ability to unwrap this additional fold-over. In SENSE imaging, it is essential to consider all contributions to a reduced-FOV pixel before SENSE unfolding. Prescribing too small an FOV amounts to ignoring contributions from outside this FOV. Thus ignored, these contributions will contaminate each of the pixels actu-

ally considered. That is why we observe equidistant ghosts of the ignored peripheral tissue, with a spacing that is equal to the reduced-FOV of the single coil data (Fig. 6).

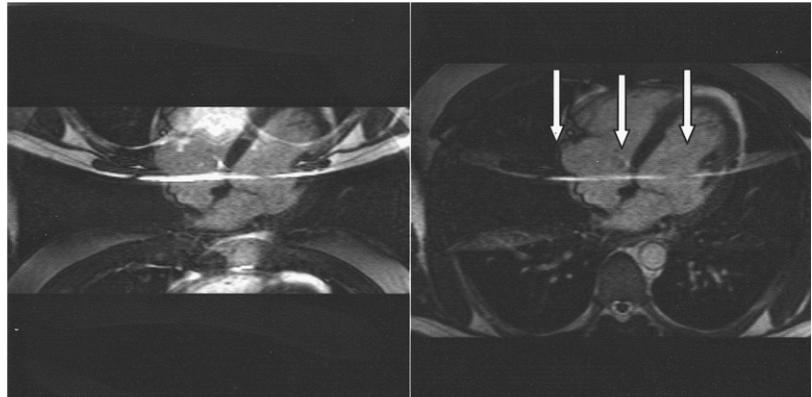
As in conventional imaging, to obtain artifact-free images, the reconstructed-FOV must be larger than the object being imaged. Contrary to conventional imaging, image artifacts are present not only at the edges of the FOV but also in the central portion. Since this artifact is often near a region of interest, clinical interpretation may be impossible or difficult. The SENSE ghost may obscure a stenosis in an angiographic application. In imaging of the heart, the SENSE ghost may obscure parts of the myocardium or mimic a nonviable region.

In practice, it may be difficult to identify the SENSE ghost and its source. Care must be taken when acquiring multiple slices, since these artifacts may occur only in a wider part of the body. In oblique MRI, the subject's arms often wrap into the FOV and may have to be raised

REDUCED FOV

SENSE

SENSE FACTOR 1.5



SENSE FACTOR 1.25

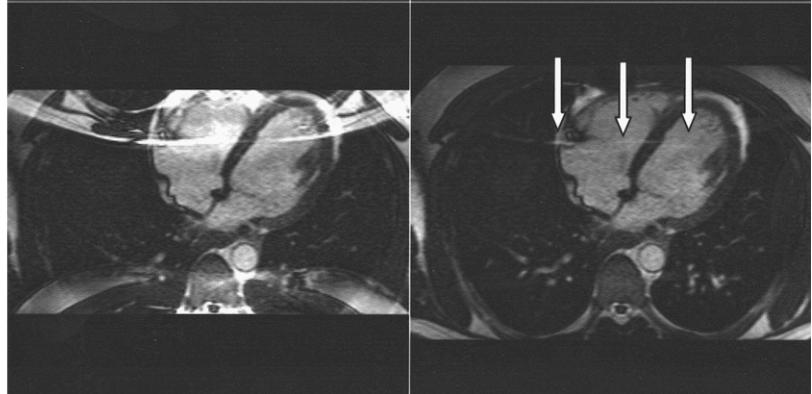


Figure 5. Axial images demonstrating the effect of the SENSE factor on the position of the SENSE ghost. The location of the SENSE ghost (arrows) depends on the SENSE factor. The SENSE ghost moves toward the edge of the image as the SENSE factor is reduced.

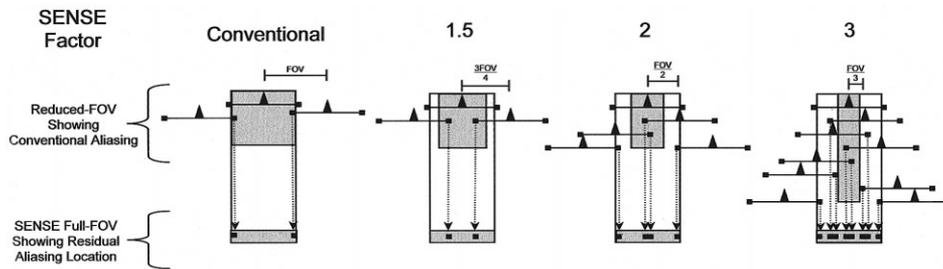


Figure 6. Schematic representation of residual aliasing artifacts in SENSE imaging. The object, \blacktriangle , extends past the imaging FOV on both sides, represented by \blacksquare . Periodic replication of the object due to undersampling in k-space is shown, and the reduced-FOV (solid rectangle) has contributions from these periodic replications. In the SENSE full-FOV reconstructions, residual artifacts are present in the same locations as the reduced-FOV. Artifacts present in a conventional acquisition at the edges of image are located at distinct locations in the SENSE reconstructions.

FULL-FOV
FOV_Z=20cm

SENSE
FOV_Z=20cm

SENSE
FOV_Z=15cm

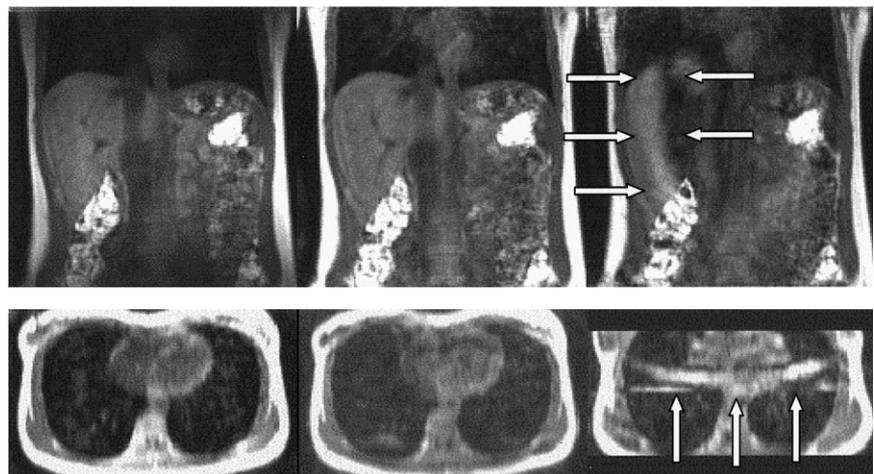


Figure 7. Coronal images demonstrating the SENSE ghost (arrows) when SENSE is used in the partition-encoding dimension of a three-dimensional acquisition. Top row: Source coronal images from the center of a three-dimensional acquisition. Bottom row: Axial reconstructions from coronal images. Due to an imperfect slice excitation profile, the artifact results from fat that is excited outside of the three-dimensional FOV.

above the head. In certain cases, SENSE imaging may not provide a substantial decrease in scan time if a conventional image can be collected with N/2 ghosting that does not obscure the area of interest. To remove the artifact, one can increase the imaging FOV, use spatial saturation techniques, change the phase-encode/SENSE direction, increase the SENSE factor to reconstruct a larger FOV, or use a full-FOV acquisition.

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