Study and implementation of the SENSE method for MR image reconstruction from multiple coils acquisition.

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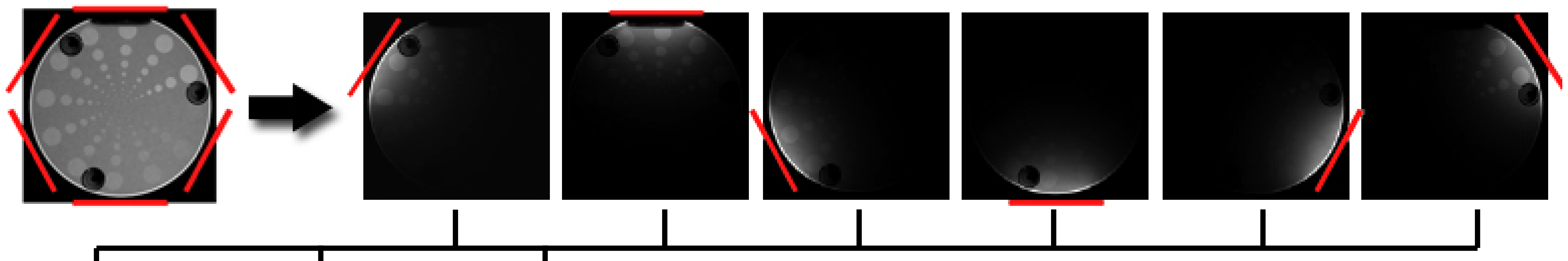
Abstract

The performance of scanners for magnetic resonance imaging (MRI) had a leap in the last decade thanks to the advent of parallel acquisition, or acquisition with multiple coils. This type of acquisition allows either reducing the time of scanning, which is always important in acquisition of medical images, particularly in studies of functional magnetic resonance imaging (fMRI); or improving the signal-to-noise ratio (SNR) of the acquired images. The aim of this work was to study the reconstruction of MR images acquired with multiple coils, particularly using the SENSE method [1]. The choice of reconstruction method was due to the fact that our institution has a 3T MR scanner (Philips), which works with acquisition through multiple channels, and performs the reconstruction through a "black box" based on the SENSE method. In order to achieve our goal, we first undertook a study concerning the physical principles of MR signal generation and the reconstruction of MR images acquired in standard fashion (single coil acquisition). Next we studied the SENSE method and the file format of the raw data output by our scanner. The SENSE (Sensitivity Encoding) method was presented by Pruessmann et al. in 1999 [1], and it is based on the fact that the MR signal measured by a detector near the sample varies significantly depending on its position. That is, knowledge about the spatial sensitivity of a detector carries information on the origin of the MR signal detected, which can be used to generate images.

Since the sensitivity is a property of the detector and is independent of the scanned object, several samples of the object with different information content can be obtained simultaneously using multiple detectors in parallel. This approach allows the reduction of the scan time without the need to increase the speed of filling the k-space. This is done by reducing the number of points in k-space, since the missing information can be obtained using the sensitivity information of the various coils. So far we have implemented routines for reading the raw data and building sensitivity matrices. Next we intend to implement the SENSE reconstruction and thus be independent of the scanner’s black box".



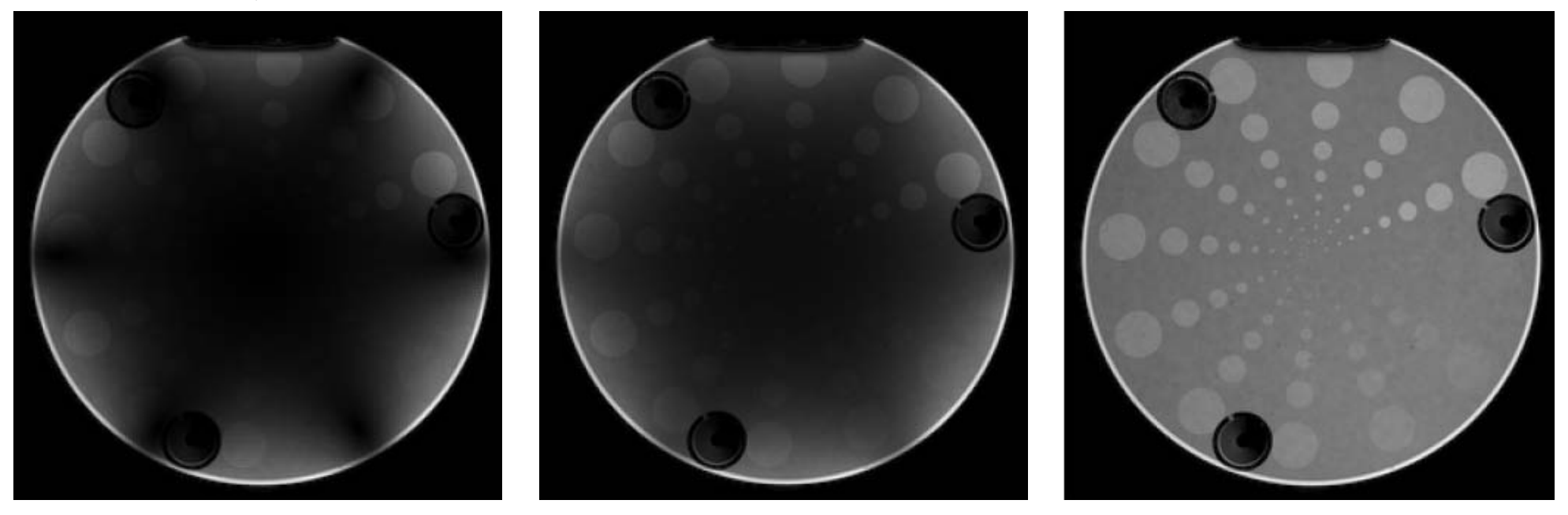


Figure 4. In the scheme above we can see in the top the resulting images of a particular combination of coils, in red. Bellow we have from left to right a single-sum reconstruction, a Sum-of-Squares reconstruction and a SENSE reconstruction of these images. It’s clear that for medical purposes SENSE is the best method.

FULL INFO. IMAGES

Reading raw .list

Organize Information

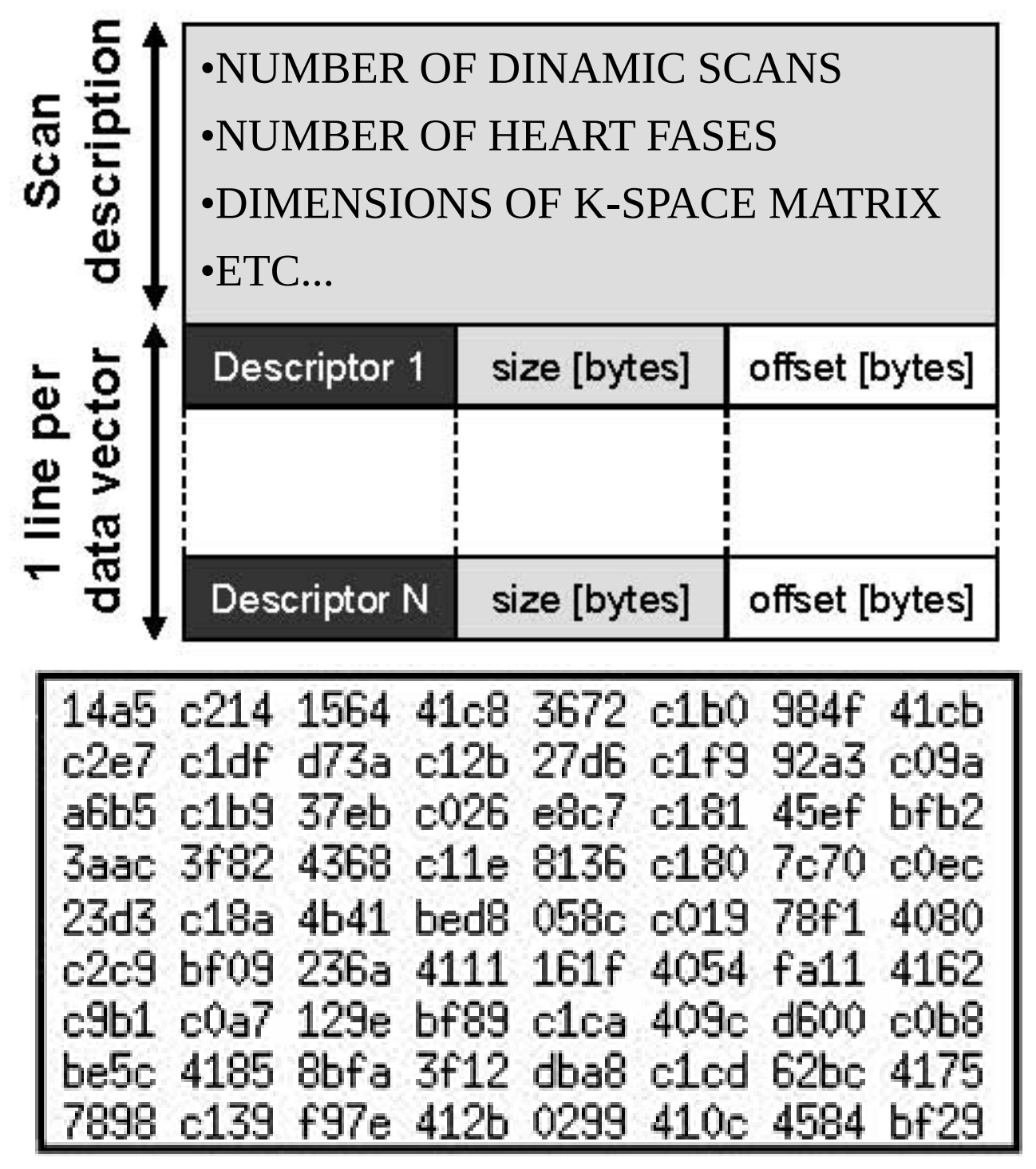
Create k-space’s
(reading raw .data)

1D FFT
(no reduced direction)

Phase Correction
(reduced direction)

FFT
(reduced direction)

Aliased Images



•NUMBER OF DINAMIC SCANS
•NUMBER OF HEART FASES
•DIMENSIONS OF K-SPACE MATRIX
•ETC...

Descriptor 1	size [bytes]	offset [bytes]
Descriptor N	size [bytes]	offset [bytes]

```
14a5 c214 1564 41c8 3672 c1b0 984f 41cb
c2e7 c1df d73a c12b 27d6 c1f9 92a3 c09a
a6b5 c1b9 37eb c026 e8c7 c181 45ef bfb2
3aac 3f82 4368 c11e 8136 c180 7c70 c0ec
23d3 c18a 4b41 bed8 058c c019 78f1 4080
c2c9 bf09 236a 4111 161f 4054 fa11 4162
c9b1 c0a7 129e bf89 c1ca 409c d600 c0b8
be5c 4185 8bfa 3f12 dba8 c1cd 62bc 4175
7898 c139 f97e 412b 0299 410c 4584 bf29
```

Figure 5. We can see how .list file is organized (top) and why .data file (bottom) must be read after the creation of NOI, STD and others vector offset maps.

REFERENCE IMAGES

Reading raw .list

Organize Information

Create k-space’s
(reading raw .data)

2D FFT recon

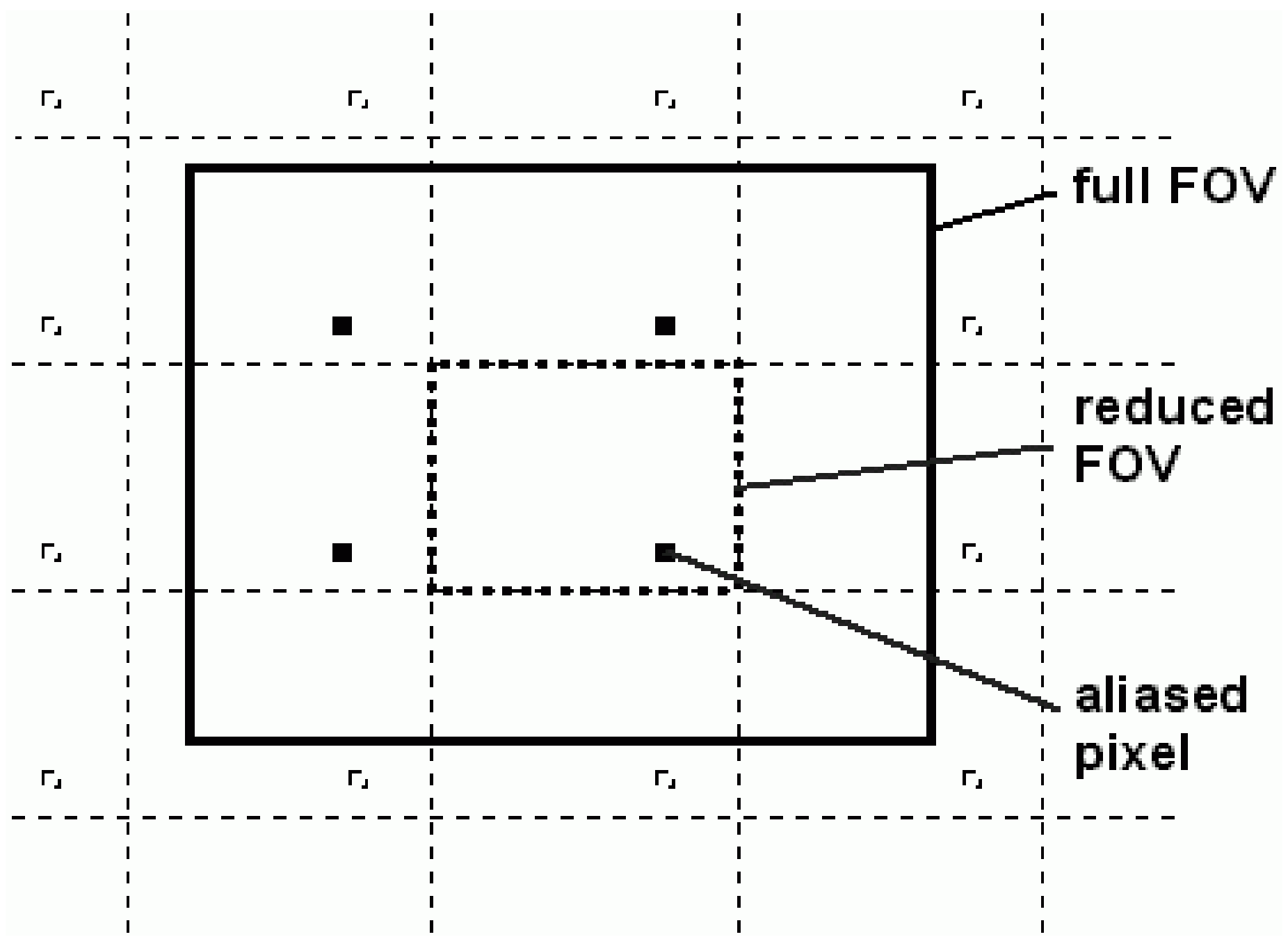


Figure 1. We can see the result of increasing the k-space sampling distance in the image above as the reduced FOV has contribution of many of the full FOV pixels.

SENSE

Sensitivity encoding (SENSE) is a technique that enables increasing the spatial and/or time resolution in magnetic resonance imaging (MRI) considerably. This is achieved by making use of the spatial information related to the coils of a receiver array – for example, to increase the time resolution this information may be traded for number of sampling positions in k-space. In this particular project, we focused on the application of SENSE to a Cartesian sampling scheme, although it can be used for any imaging sequence and k-space trajectory.

In 2D Fourier imaging with common Cartesian sampling of k-space sensitivity encoding by means of a receiver array enables to reduce the number of Fourier encoding steps. This is achieved by increasing the distance of sampling positions in k-space while maintaining the maximum k-values. Thus scan time is reduced at preserved spatial resolution. The factor by which the number of k-space samples is reduced is referred to as the reduction factor R. In standard Fourier imaging reducing the sampling density results in the reduction of the field-of-view (FOV) (1) , causing aliasing (2). In fact, SENSE reconstruction in the Cartesian case is efficiently performed by first creating one such aliased image for each array element using discrete Fourier transform (DFT), as we can see in the figures below.

NOISE MATRIX

For an optimal SNR, the scanner measures a large number of samples with pure noise from each channel and we use these to calculate the level and correlation of the noise from each coil on a covariance matrix. This matrix, Ψ , is then used to minimize the noise effects of a single coil in the final reconstruction. We can use an identity matrix for Ψ if we don’t have enough data or for study.

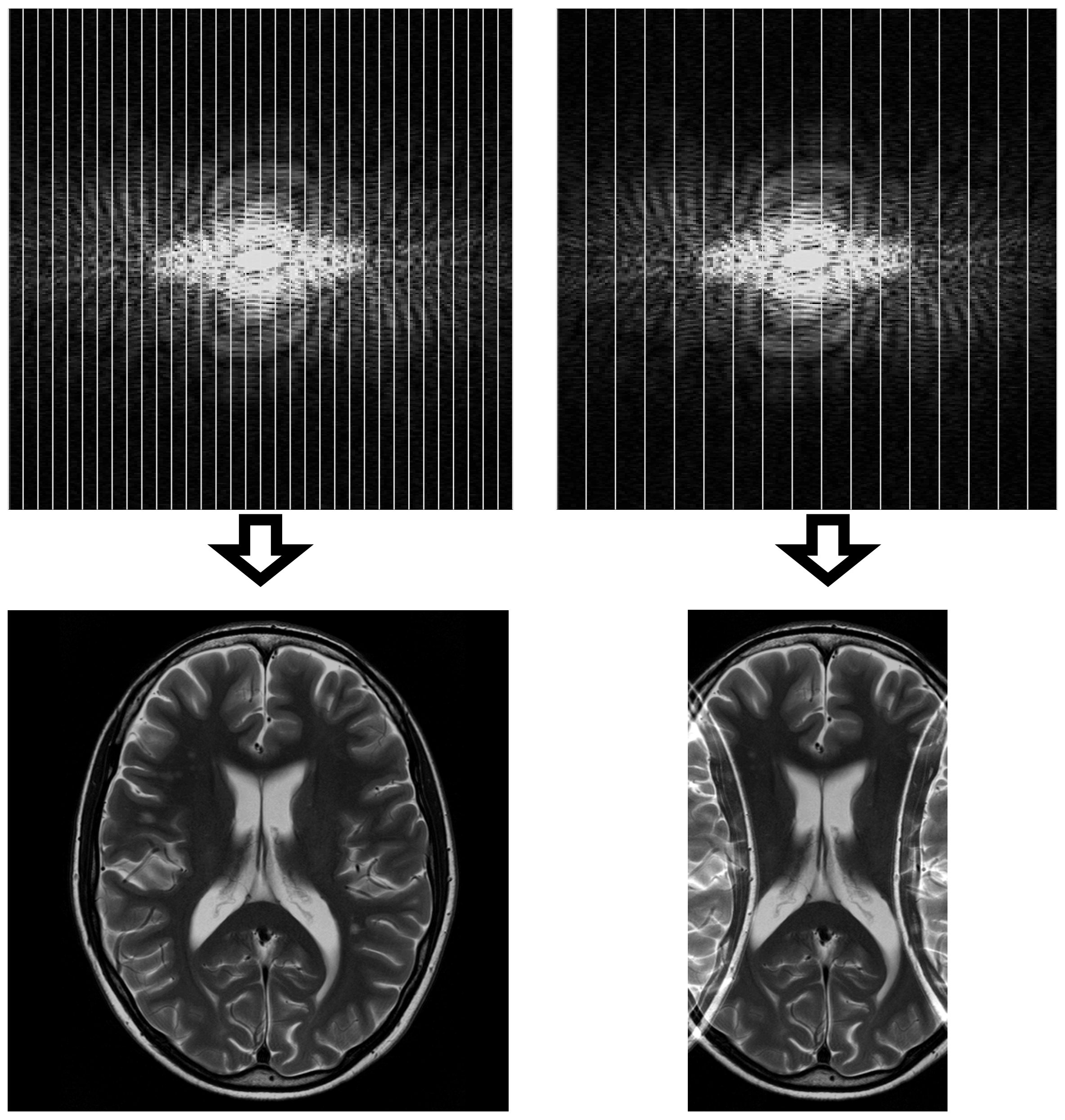


Figure 2. Top: we can see the normal sampling (left) and with an R factor = 2 (right). Bottom: the result after full FFT.

SENSIVITY MAPS

Artifact-free SENSE reconstruction relies on accurate knowledge of the individual coil sensitivities. For sensitivity assessment, low-resolution, fully Fourier-encoded reference images are required, obtained with each array element. Element-wise division of the array references by the Sum-of-Squares yields raw sensitivity maps (for more precise sensitivity images, a body coil image should be used instead of the Sum-of-Squares). Raw sensitivity maps are refined by a fitting procedure which performs noise elimination and sensitivity extrapolation. Regions which, according to the references, do not contribute significant signal, can be automatically excluded from SENSE reconstruction. Thereby, it is taken into account that the true degree of aliasing is locally reduced when one or more aliased components are zero.

UNFOLDING MATRIX EXPLANATION

Unfolding is possible as long as the reduction factor does not exceed the number of coils used. The reason for that is to ensure the inversion of the matrix in the unfolding equation. Now, in possession of the Sensitivity Maps **S**, the Aliased Images and the Noise Matrix **Ψ**, we calculate from each set of aliased pixels **A**, the most precise contribution of each pixel of the set to the final image, ρ.

$$\mathbf{U} = (\mathbf{S}^{H}\ \Psi^{-1}\ \mathbf{S})^{-1}\ \mathbf{S}^{H}\ \Psi^{-1}$$

$$\rho = \mathbf{U} \cdot \mathbf{A}$$

The scheme below shows a representation of this procedure. Repeating the same procedure for each set of aliased pixels, we have a final non-aliased image with full resolution and at a much shorter scan time.

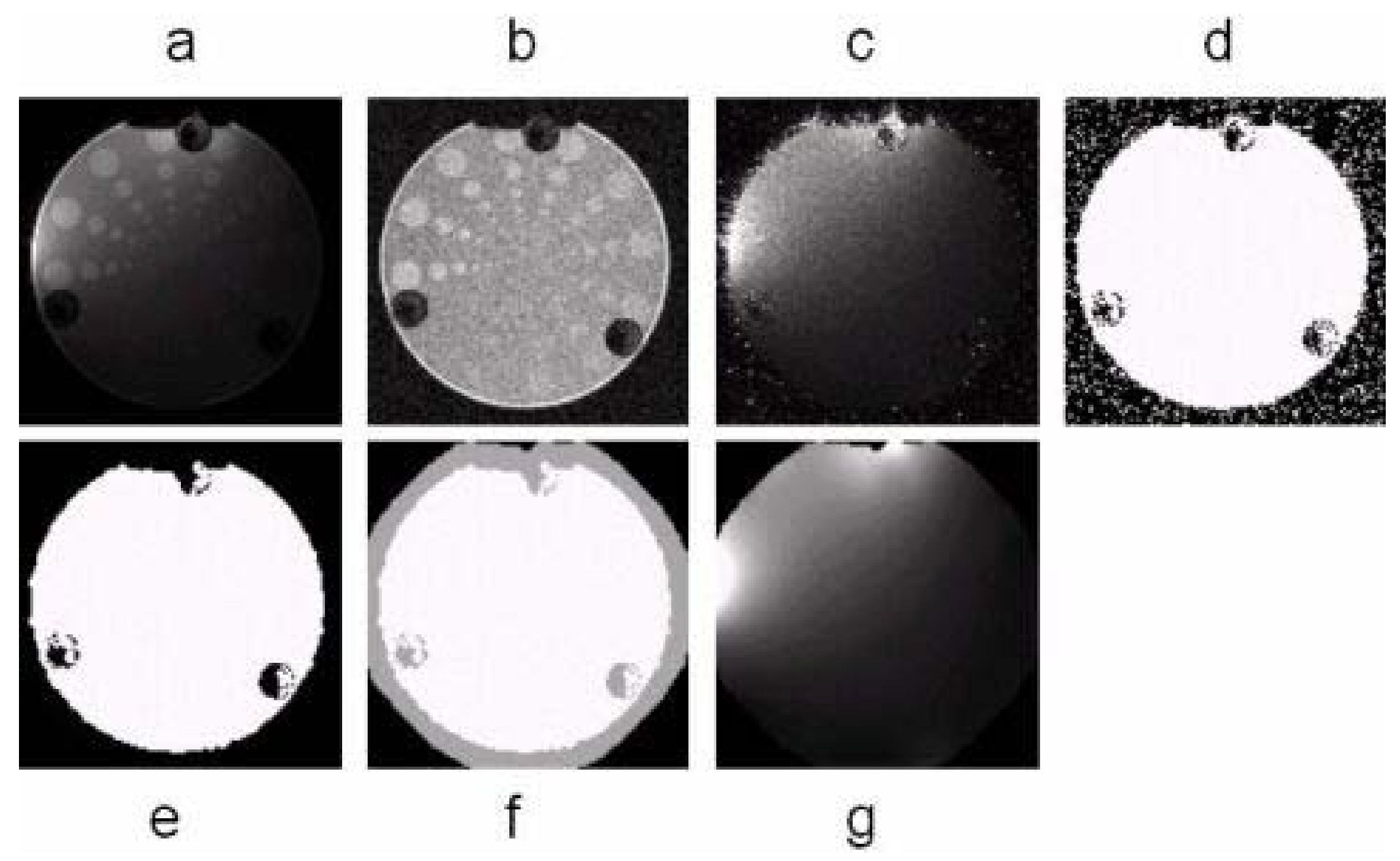


Figure 3. We can see the process of determination of sensitivity maps in the images above. Division of a surface coil image (a) by a body coil image (b) of the same slice yields a raw sensitivity map (c). Regions exhibiting pure noise are identified by thresholding (d) and subsequent density filtering (e). The extrapolation zone is determined by region growing (f). Local polynomial fitting yields the refined map (g).

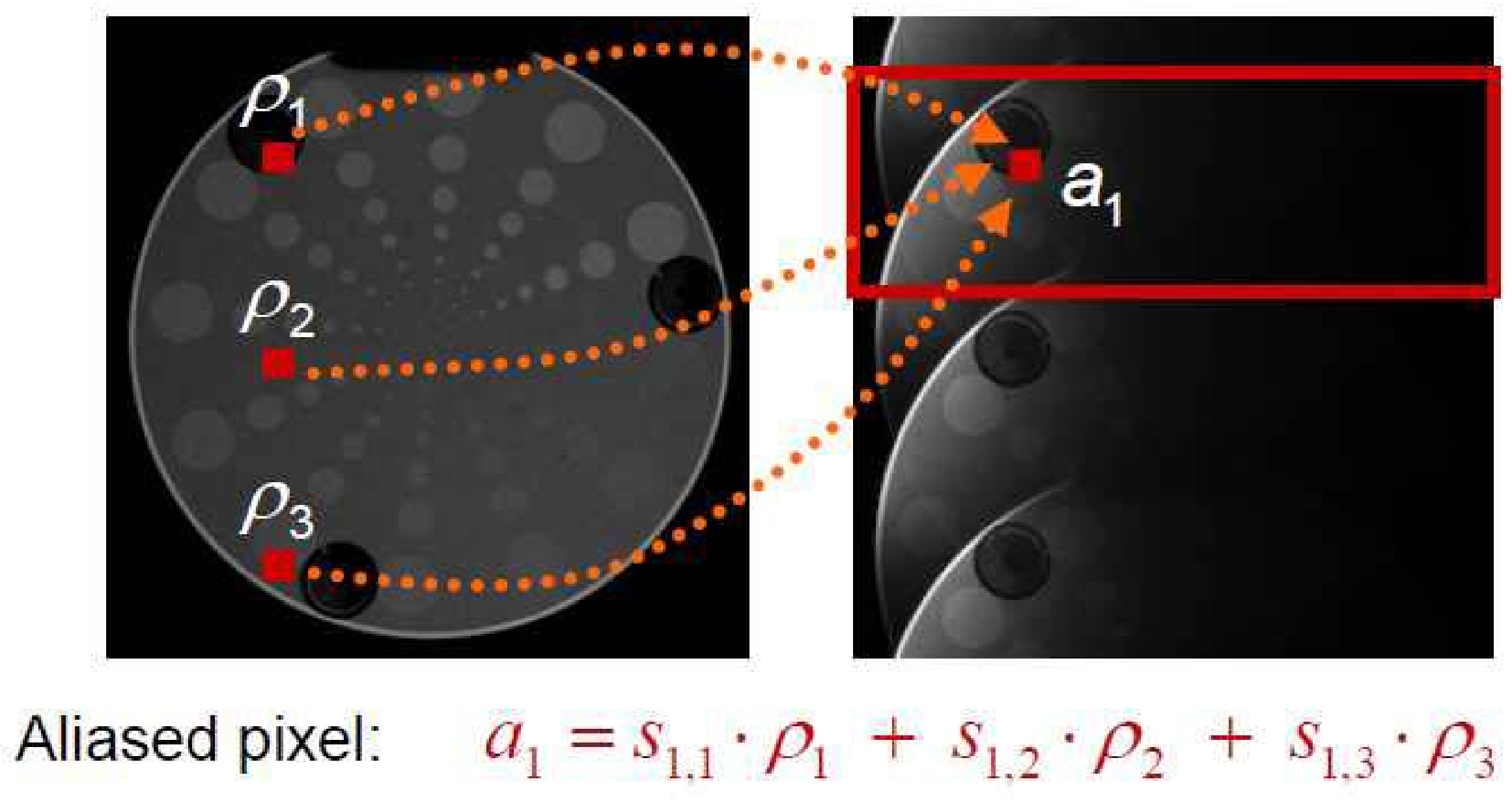


Figure 6. For a reduction factor R = 3, each pixel a in the aliased reconstructed image is a combination of 3 pixels in the “true” full-FOV image.

References

[1] Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: Sensitivity Enconding for Fast MRI. Magnetic Resonance in Medicine 42:952-962, 1999.

[2] Roemer PB, Edelstein WA, Hayes CE, Souza SP, Mueller OM. The NMR phased array. Magnetic Resonance in Medicine 16:192–225, 1990.