

A Pixel is an Artifact: On the Necessity of Zero-filling in Fourier Imaging

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Introduction: Although image display of Fourier-acquired data is fundamental to MRI, the literature on the topic is rather sparse relative to its importance. We present here an approach to analyze the *actual visual scene* presented by a 2D array of finite-sized squares of uniform intensity ('image pixels'). It is, after all, the visual representation on the display device that determines the image interpretation by an observer. The key point is that although the discrete 2DFFT algorithm provides a transformation of sample raw data into a set of points in the spatial domain, it does not directly address the representation of this information as a continuous visual display ('image'). That is a separate matter.

The Problem: The problem is that a common approach to image display - in which each data point from the 2DFFT is used to assign the intensity of a square patch of the display device - performs poorly when the individual patches are visible. Although this might seem an old issue, we argue that it is a topical concern: in a randomly-selected recent issue of MRM (print edition) small squares are visible in 14 figures and even on the cover page (1).

The first problem with this display mode is that it is not unique. Consider Fig.1a which shows a zoomed-in portion of an image with the individual pixels clearly visible. Fig. 1b-d are results of shifting Fig. 1a half a pixel in three different directions (achieved by applying linear phases shifts in k-space). Inspection of this figure shows that a single k-space dataset can produce very different visual display. There is no basis for choosing one such display over another.

Methods: To quantitatively evaluate the patchwork display mode we designed a Fourier-based method to decompose a pixelated visual scene into two parts: one representing the information in the original MRI k-space data ('signal'), and the other all the visible structure related to pixelated patchwork display ('pixelation artifact') (Figs.2 & 3). The method involves re-sampling the patchwork visual scene at very high resolution to analyze the actual visible spatial frequency content. Fig.2. shows this decomposition for a single k-space coordinate -by performing this repeatedly, k-space maps showing levels of pixelation artifact and signal loss were derived. Figure 3 shows the decomposition performed on image Fig.1a.

Results: Figs.2b and 3b represent high spatial frequencies present in the visual scene, but not in the original k-space. It can be seen that Figs.2a & 3a deviate from Figs.2c & 3c due to: 1) the creation of the artifactual patch edges; and from 2) the suppression of real structure within each patch. The k-space maps also show these two effects: (1) introduction of artifactual high frequency image structure; (2) attenuation of higher spatial frequencies. **Signal Map:** (not shown) the k-space signal map shows an almost radial loss of signal visibility, ranging from 100% signal (no loss) at the center of k-space to 65% signal at $(K_x, K_y) = (N_k, 0)$. The signal visibility level goes down to 42% at the corner of k-space, (N_k, N_k) . Signal visibility is at 81% at $(N_k/2, N_k/2)$, which is the furthest-out non-zero location if a zero-fill factor = 2 in each spatial dimension is used. These losses represent the limitations of the pixel array in representing higher spatial frequencies. **Artifact Map:** (not shown) the artifact map starts at zero at the k-space origin, increasing almost radially. **Signal-to-Artifact Ratio (S/A) Map:** (shown in Fig.4) is formed by the ratio of the 2 previous maps. At $(N_k/2, N_k/2)$ S/A = 69%; at $(N_k, 0)$ S/A = 110%; at (N_k, N_k) S/A = 210%.

Solution by zero-filling: The effect of zero-filling is to cause the acquired data to lie closer to the origin of the k-space maps, where the artifact-to-signal ratio is lower (Fig.5). The coverage of acquired (non-zero) k-space is shown as a shaded area. In NMR spectroscopy Bartholdi & Ernst (2) analyzed the special case of zero-fill by a factor of 2. Lindon & Ferrige show that there are situations in which a zero-fill factor as high as 32 can be beneficial in resolving overlapping peaks. Our findings are in accord with this latter result. The most relevant MRI work has been by Bernstein et al. in their discussions of the corners of k-space (4). The use of high levels of zero-fill (ZF) are illustrated in the Figs.6 & 7, which shows simulated image results from a phantom image of ZF levels 0, 2, and 4 in k-space. From Figs.6&7 b-d, it is clear that the higher zero-fill, the less effect of the pixelation artifact.

Discussion: Zero-filled images show genuine image structures without introduction of high frequency visual artifacts. In some cases ringing artifacts may be more clearly visualized following zero-filling. They are also present in non-zero-filled images, but not distinguishable from real structures. It is beyond the scope of this work, but we hypothesize that the clearer visualization of ringing is beneficial (as a first step) because ringing needs to be clearly identified before any solutions can be implemented.

Conclusion: A square patch of uniform intensity ('pixel') is an artifact because such structures exist neither in the object being imaged, nor in the raw k-space data. Zero-filling is able to eliminate these effects in Fourier imaging so that only the acquired spatial frequencies are visualized.

References: (1) Magn. Reson. Med 2010 63(1). (2) Bartholdi E, Ernst RR. JMR 1973;11(1):9-19.; (3) Lindon JC, Ferrige AG. Prog. in NMR Spectroscopy 1980;14 :27-66.; (4) Bernstein MA, et al. SJ. JMIR 2001;14(3):270-280.

