Rose model in MRI: noise limitation on spatial resolution and implications for contrast enhanced MR angiography

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Introduction

The relationship between noise and detectable spatial resolution is described by the Rose Model: the differentiation of a single voxel from the noise background requires a minimum signal-to-noise ratio (SNR) per voxel of 4 (1,2). This model has been widely used as a guide in x-ray imaging. This study assesses its implication for MRI and develops a guideline for k-space sampling.

In k-space, the signal falls off rapidly with k-space radius whereas the noise power is constant over the entire frequency range (2). Increasing the sampled volume of k-space increases resolution at the expense of decreased image SNR. When the SNR is reduced to the Rose limit (~4), the detectable resolution ceases to increase. This noise limit on detectable spatial resolution indicates that there is a cutoff k-space radius corresponding to maximum resolution and optimal scan time.

Optimizing k-space and scan time is particularly important for contrast enhanced MRA (CEMRA). Many techniques such as timing, undersampling and view ordering have been developed to maximize the contrast enhancement at the k-space center (3). How big is the center of k-space? The Rose model is used to answer this question.

Methods and results

Rose model. The original Rose criterion requires direct measurement of the voxel SNR (statistical properties) and the voxel conspicuity (human observation). The former criterion can be considered as a statistical test for a hypothesis that the probability distribution of the signal intensity in one voxel is significantly different from that of the background. The probability distribution can be obtained from many repeated experiments, which are not realistic to perform. To overcome this problem, a uniform phantom can be imaged once, and the statistical distribution can be estimated from the voxel intensities over a large area of the uniform phantom.

Such statistical analysis provides a link to express the Rose criterion in k-space. To measure signal and noise in k-space, two nominally identical acquisitions $m_1(k)$ and $m_2(k)$ were obtained from a uniform spherical phantom. Complex subtraction of the measurements, and taking the mean-square average within an annulus of radius k_r in k-space yields the RMS noise, $\sigma(k_r)$.

$$\sigma(k_r)^2 = \frac{1}{2} <|m_1(k) - m_2(k)|^2>$$

while taking the mean-square values from a single measurement gives the RMS signal, $S(k_r)$.

$$S(k_r)^2 = <|m_1(k)|^2> - \sigma(k_r)^2$$

Figure 1 shows the measured k-space SNR for a 512x512 acquisition from a uniform spherical phantom using a body coil and a fast gradient echo sequence. As the acquisition moves towards the edge of k-space (from b to e), the kSNR $= S(k_r)/\sigma(k_r)$ decreases as approximately $k_r^{-3/2}$, the voxel SNR (vSNR) decreases, and the histograms of noise and signal broaden and overlap. The detected image resolution (phantom edge) first increases with sampled k_{max} (from b to c, where there is no overlap between noise and signal histograms) and then starts to be noise limited (d, 9.8% overlap, and e, 28.8% overlap). The image quality of e is substantially inferior to c&d. The optimal detected resolution (~1.5 mm) is achieved somewhere between c&d, corresponding to vSNR ~ 4 and kSNR ~ 0.05.

The same cutoff kSNR value was also obtained using a head coil with a 3-fold increase in detected optimal resolution

(~0.5mm). This result indicates that the optimal acquisition time (k-space size) in MRI is determined by signal and noise strength.

Optimal k-space size for CEMRA. The Rose model can be used to determine the optimal k-space acquisition for CEMRA. For human subjects, physiologic motion prevents quantitation of signal and noise. Instead, measurements were made by post-acquisition filtering to simulate a reduction in scan time. Clinical CEMRA data was filtered, and experienced readers assessed the clinical utility of the images obtained.
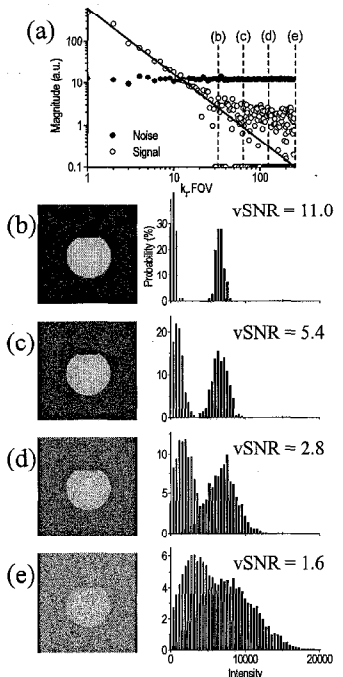

Figure 1. (a) RMS signal and noise vs. kr. (b)-(e) images and corresponding pixel intensity histograms with k_{max}.FOV values of 32, 64, 128 and 256.

For typical abdominal aorta studies using a body coil and fast 3D gradient echo sequence (TE/TR = 1/5 msec), all clinical significant features were clearly depicted for reductions in the scan time of up to 50%.

Application to peripheral MRA. A 40% reduction in scan time in the fast 3D sequence was implemented by sampling a cylindrical volume of k-space. This sequence was used for bolus chase CEMRA acquisition in the lower extremity. With reduced contrast dose (20%), the shortened acquisition provided better depiction of the renal arteries in the first station (due to shorter, therefore better, breathholding), higher SNR for the distal station (due to better timing of the acquisition to the bolus transit), and also reduced venous signal in the distal stations.

Conclusion and discussion

Noise limits spatial resolution in fast MRI; the optimal resolution (and optimal acquisition time) is achieved at kSNR ~ 0.05 (Rose Model). The acquisition time in current body coil CEMRA may be reduced without losing diagnostic information. Developments of CEMRA should be directed to improving signal strength (contrast agent relaxivity, coil sensitivity, etc).

References

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