Wideband MRI: Theoretical Analysis and Its Applications

E. L. Wu, J-H. Chen, and T-D. Chiueh

Abstract:
Wideband MRI, a novel technique that utilized expanded bandwidth with several carriers, has been demonstrated to increase the throughput of MR imaging. Various MR imaging methods, especially those that require large coverage, have successfully taken advantage of Wideband MRI and obtain speedup as high as to 8X. The fundamental physics of Wideband MRI was inspected from basic equations derived in this paper. Not only evaluating the pros and cons, but also provide guidelines for parameter designs.

Two possible ways to apply Wideband MRI is done in this study. One is to accelerate the total scan time of a whole body study, and the other to obtain images with finer detailed information without consuming excessive time. In either experiment, Wideband MRI proves itself to be a powerful tool for the evolution of MR imaging and biomedical imaging as well.

Keywords: Bandwidth, 3D, MRI acceleration

I. Introduction
Faster MRI acquisition has always been an unceasing pursuit of all MRI practitioners. A plethora of fast acquisition methods has been developed for the past few decades, from Multi-Slice Multi-Echo to parallel imaging. Acceleration methods of MRI have exploited in both temporal and spatial domains. However, the usage of signal bandwidth in MRI equipments remains to be highly inefficient compared to its radio frequency sibling in wireless communications, another technology based on radio frequency signals, which has increased by 1000 folds, from 10k bit/s to 10M bit/s in the last two decades. [1]

From a frequency perspective, MRI excites and receives a single frequency band for each image. To efficiently exploit the bandwidth, multiple frequency bands are to be both excited and acquired at the same time. Similar attempts of this groundwork have been done previously, by either using added hardware [2] or modified sequences [3]. The hardware used in the former method lacks flexibility thus greatly limits the feasibility while the latter suffers from image quality degradation in forms of image blurring. We tackle the issue with the understanding of communication and signal processing principles to identify the mechanism, and propose a simple remedy that may overcome the problems that previous researchers fail to achieve.

Wideband MRI RF pulses contains several bands, we define the number of bands as “Wideband multi-slice/slab factor W”. Adding a separation gradient during the spatial encoding process labels each band with a unique carrier frequency, making the resonated signal also wide-banded. It is the excitation / acquisition of this wideband signal that provides additional information that makes acceleration possible. Fig. 1 below is a conceptual illustration of a W factor=5 human whole body scan. By simultaneously exciting 5 different locations and receiving the Wide-banded resonance signal, the image derived from the acquired signal will contain images arranged side by side from position 1~5 in one single scan.

Fig. 1 Conceptual illustration of a Wideband MRI human whole body scan with Wideband factor W=5.

We start the study from the basic MRI signal processing. Equation (1) is the signal in k-space derived from the proton density distribution along one single k-line.

\[ S(k_x, k_y) = \int \int \rho(x, y) \exp\{2\pi(k_x x + k_y y)\} dx \, dy \, dk_x \, dk_y \]  (1)

Here we see the final signal comes from the excited proton density distribution function \( \rho(x, y) \) undergoing the process of spatial encoding and integrated along all 3 dimensions. Shown in Fig. 2 is the spatial encoding process of a conventional 2D MRI (left) and a Wideband 2D MRI sequence. In Wideband MRI, an additional separation gradient (in red line) is applied while a spatial encoding gradient is deployed. The duration of the separation gradient is the same as one of the spatial encoding gradients, \( G_x \) in this case. \( k_x \) & \( k_y \) are the coordinates of the image-frequency space (usually known as k-space), and the output image is the 2-dimensional transform of the k-space.
As we include the factor of the added separation gradient into the MRI signal equation (1), an extra $k_y$ appears and is integrated over the image slice thickness. The final MRI signal is shown below, where $S(k_x, k_y)$ is the original MRI signal without separation gradient applied. $R$ is the ratio of $G_y/G_x$, this is the slice thickness, $Z_{cen}$ the center position of each slice of image

$$S'(k_x, k_y) = S(k_x, k_y) \cdot \text{Sinc} \left( \gamma G_z \tau \left( \frac{f_b}{2} \right) \cdot \exp \left[ j \gamma G_z \tau Z_{cen} \right] \right)$$

$$= S(k_x, k_y) \cdot \text{Sinc} \left( \alpha k_x \right) \cdot \exp \left[ j \beta k_y \right]$$

As shown in (2), there are two additional terms contributed from the extra $k_y$ that makes the resonance signal of Wideband MRI different from that of conventional MR imaging. The exponential term indicates a shift in the image space, a circular shift to be precise. For each excited slices, the resulting image will become more and more drifted away from the center of the field of view as the slice position is moved away from the center of the slice selection gradient. It is worth mentioning that the separation gradient can be applied during either spatial encoding gradients, phase encoding or frequency encoding or even both. As a result, the separation between the slices/slab excited will be along the direction where the separation gradient is added, and a diagonally separated image will be produced with separation gradient present during both spatial encoding gradients.

$$\Delta x_j = \left( \frac{G_z}{G_x} \right) (Z_{cen2} - Z_{cen1})$$

Calculated in (3), the amount of shift $x_j$ has a simple relation between the separation / spatial encoding gradient ratio, the distance between excited slices, and has to be greater than the field of view / width of the image in order to fully separate the different slices excited simultaneously without overlap. This can be interpreted by a geometrical perspective, to see the effect as an outcome of sheared voxels.

Fig.2 Spatial encoding and signal acquisition of normal 2D MRI (left), and Wideband 2D MRI (right) sequences. The added separation gradient can be placed either during $G_x$ or $G_y$, causing a different shifting direction.

This perspective was used in previous studies where the mathematics in signal processing was unknown.

The added Sinc term acts as a filter. By multiplying a Sinc function, the $k$-space is being processed by a low-pass filter. The intensity of higher frequency terms (larger $k$ values) were being attenuated by the envelope of the Sinc, which is seen as image blurring. The determining factors of the sinc function are the separate/readout gradient ratio, slice thickness, and the total acquisition time. Increasing the separation/spatial encoding ratio and slice thickness directly causes the Sinc function to turn sharper and have zero crossings closer to the center. Understanding the effect of such process helps us design experiment methods to mitigate the additional effects while preserving information contained in the images.

With the knowledge of Wideband MRI mathematics and the factors that cause image blurring, one simple remedy is to decrease slice thickness. Slice thickness in 2D MRI is determined by the intensity of slice selection gradient strength and bandwidth of RF pulse. The gradient strength has an upper limit as well as the response time of RF module which also confines the value of RF pulse bandwidth. On the other hand, slice thickness issue can be simply solved by 3D imaging where the actual slice thickness can be primarily determined by steps of encoding along slice direction instead of physical constrains. Wideband 3D MRI follows the same rules of 2D, and has the same effect derived from (2). With carefully selected parameters, Wideband MRI accelerated images can be acquired without incurring any visible degradation in image quality.

**Material & Methods**

It is apparent that wideband MRI is a promising acceleration method for applications obtaining large coverage such as whole human body screening. Such benefits are the key to whole body MRI diagnosis and cancer metastases research. However, conventional RF coil designs and RF homogeneity of the coil are designed and optimized for limited volume in human imager and is, therefore, not appropriate to demonstrate this specific application. Here we use animal imaging platform as the pilot to provide the coverage necessary for mice whole body scan, $W=6\&8$ scans were chosen over the long geometrical shape of a mice and the optimal spatial resolution.

A mouse with total length of around 9 cm was positioned in the volume coil. Field of view is 3.5 cm width x 2.5 cm height, matrix size=256x192, achieving a very high resolution of .13mmx.13mmx.176mm. Imaging parameters are the same for $W=6\&8$ scans. Excitation pulse of Wideband MRI was calculated and synthesized according to the geometry of the total coverage and desired Wideband acceleration factor. The overall bandwidth was increased proportionally with the Wideband acceleration factor used, $W=6$ and $8$ respectively.

Aside from viewing Wideband MRI as an approach to accelerate total scan time over a large area, the other view is...
To increase spatial resolution in thickness using the same time. To show the benefits of higher resolution images taken within the same time using Wideband MRI, a set of W=2 brain image was taken in comparison with a set of normal brain image. The images were taken using the same scan time while W=2 Wideband MRI images has a 2X spatial resolution along slice direction (half the image thickness). Imaging parameters are as follow: TR=34ms/TE=6ms for both settings; spatial resolution is 1x1x2mm³ for normal MRI sequence, 1x1x1mm³ for W=2 Wideband MRI.

The mice whole body image was performed on a Bruker 7T Biospec animal system using a single-channel volume coil. The high-resolution comparison was done on a 3T Bruker Biospec system with a T8826 head coil.

Results

Shown below in figure 3 are the W=6 and W=8 images. Each image contains number of slices of different locations of the mice according to the Wideband factor used. From the head through chest and abdomens until bladder and hinder feet, all slices were evenly spaced in the outcome image. A total 512 slices of high-resolution axial images were acquired. For the W=6 acceleration, single scan time is around 10 mins while it only takes 7 mins for the W=8 scan. It could take an hour for conventional methods to take the whole body image with such a high resolution.

In the experiment to use Wideband MRI to increase spatial resolution in human brain scan, the images were displayed in Figure 4. Axial slices around the lateral ventricle was zoomed up and compared.

Discussion

As we have mentioned above the total bandwidth usage has increased. However, bandwidth per slice still remains the same as normal 3D imaging thus explaining the SNR consistency. Also image SNR along the whole mice is quite uniform, due to the size of the mice fits within the homogeneous zone of the RF coil. As for human studies, larger coils with larger coverage will be needed for higher Wideband factor imaging. However, the coverage issue might be easily overcome by traveling wave MRI, a new technique that breaks through the limits of RF coil shape and size.

The images shown were obtained with sacrificed mice; images using in-vivo mice images were also taken but suffer from motion artifacts. Respiratory gating might reduce such effects but mouse responds irregularly to anesthetics, making complete removal of the artifacts around chest difficult. In human imaging, respiratory artifacts can be suppressed to an extent by controlled breath holding of patients.

Conclusion

By deriving the equations we are able to understand the basic principles of Wideband MRI and the effects that it brings to the original image. Three main factors determine the filtering process by the sinc function. We solve the issue by implementing 3D scanning to reduce slice thickness and avoid image blurring.

After clarifying the use of Wideband MRI in 3D, we demonstrate the potential to perform ultra-fast high-resolution mice whole body screening using Wideband MRI technique. Two sets of results display the wideband accelerated image of a whole mice with wideband acceleration factor “W” of 6 and 8. Total scan time was dramatically reduced from around 1 hr to 10mins (W=6) and
As we have pointed out in our previous results, the reduction of scan time can be pushed further with the combination of parallel imaging techniques[6]. Once the whole body scan time drops below several minutes, quantitative molecular imaging, a faster whole body dynamic contrast enhancement, and cancer metastasis study with thinner slice thickness will become practical for MRI.

Apart from the anatomical imaging we have obtained with Wideband MRI, this technique possesses a great versatility. Not only can Wideband MRI be applied to anatomical studies, it can also be adapted to other advanced sequences[3,4,5]. Functional studies using echo planar imaging and diffusion tensor imaging can be taken either with less time or with finer details. And a great deal of new applications will arise with this improvement. Also by using Wideband MRI to improve spatial resolution, we are able to obtain images with 0.3-0.4 mm thickness in the shorter acquisition time[3,4]. This means that by applying Wideband MRI in this fashion, one can detect diseases in a far earlier stage where anomalies in image were averaged and neglected in low spatial resolution images.

We believe Wideband MRI lays a solid foundation for the future generation MRI, where the increased temporal/spatial resolution will contribute greatly to whole body screening, early cancer detection and other countless new MRI applications. It took decades for CT to evolve from single slice to 256-slice using the same paradigm and now is the time for MRI to experience another evolution.

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