Why UHF MRI? A Personal Journey from Artifact to Anatomical History

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Since I work in an ultra-high-field (UHF) MRI[1] facility, I often give tours. Obviously, a common question is, "What are the advantages of higher magnet fields?" It is easy to answer this by rattling off the usual reasons: Higher signal-to-noise ratio (SNR), which can be used for higher image resolution, faster scan times, etc., as well as better spectral separation for Magnetic Resonance Spectroscopy (MRS). You can then talk about quantitative susceptibility mapping (QSM) and the anisotropic susceptibility of white matter, which even goes as far as being dependent on the orientation of the subject's head to the field [1]. This was an unexpected contrast at 7T, which proves that you shouldn't rely entirely on expectations when attempting new experiments. After all, it wasn't so long ago that people thought higher field MRI would be absolutely impossible due to RF penetration effects.

However, I would like to describe a different journey – one in which an artifact becomes anatomical history.

When setting up prototype equipment, you end up spending a lot of time at the console, often repeating the same types of scans over and over, looking to improve performance, reduce artifacts, and so on. Since T2*-weighted imaging is particularly interesting at 7T, I have seen many, many examples of these scans. Soon after starting to work at Neurospin (Saclay, France), certain things began to catch my eye – in particular, a pattern of parallel lines that often appeared on sagittal views of the corpus callosum (CC).

Initially, I dismissed this as an artifact. UHF is very attractive in many ways, but the higher SNR can also show up artifacts. In this case, I presumed that eye movement during the scanning was causing ripples in the phase encode (PE) direction, particularly as the PE direction was generally set to anterior-posterior (AP) in order to allow a head-feet (HF) read direction, which in turn avoided fold-in from the neck or shoulders.

Somehow, though, this explanation did not satisfy me. I started looking more closely, and had the impression that the parallel lines, which appeared somewhat radial in direction on a sagittal image, were reproduced in neighboring slices. When I studied this more closely, I found that, with the protocol I was using, I could best see the stripes on slices that were slightly off the midline by one to two centimeters. Even then, the stripes could be elusive. One experiment I tried involved two parallel slices with two repetitions. The results showed these fine lines in both slices on the first repetition, but on the second repetition they only appeared on one (Fig. 1).

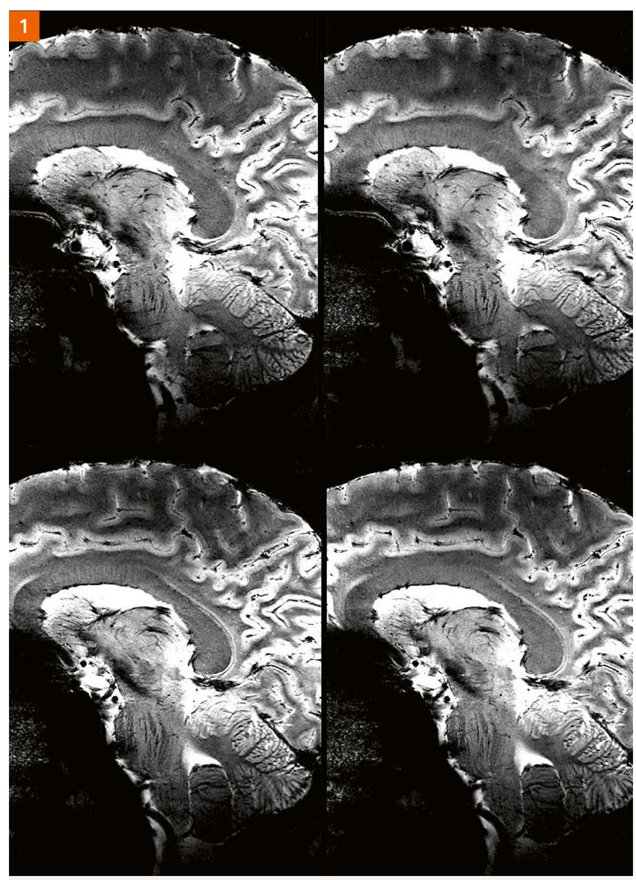

Figure 1:
Two 2D slices imaged with two repetitions as a single GRE scan. On the upper row are the two slices, with the repetitions below. The stripes can be seen in both slices in the first repetition, but only in one (bottom left) in the second.

[1] *MAGNETOM 7T is for research only. All data shown are acquired using a non-commercial system under institutional review board permission.*

However, this was still enough to convince me that there was really something in the data – but what was it we were seeing?

As I discussed this with colleagues, some more information and examples came forth. I remember a colleague presenting me with a 7T advertising, where these lines were clearly visible. Another colleague simply went to his office and picked up an anatomical atlas and – *voila*! – the CC was drawn with a similar set of radial lines. Indeed, a simple web search will bring up the Wikipedia page for the CC, which shows the *Gray's Anatomy* [2] drawing with exactly the pattern I was seeing.

Now I had to work out whether this was really the same thing. The devil's advocate in the discussion – Denis Le Bihan – argued that relying on these old atlases was putting me on shaky ground. The drawings could show the anatomist's or artist's preconceived ideas of how these structures *should* look, or they could even be inherited from earlier atlases. So the comparison was intriguing, but not definitive. We also looked at the spherical decomposition of DTI data, but saw nothing that supported any structure beyond the main L-R fiber direction.

The next step was to bring in an expert. We consulted a local neuroanatomy professor, but the answer was that there was no known structure in the CC. In other words, we were seeing an artifact.

Shortly afterwards I was invited to give a talk at the Max Planck Institute for Human Cognitive and Brain Sciences (CBS, Leipzig, Germany). I included my slide with the two-slice, two-repetition experiment to see if anyone had any insights beyond the artifact hypothesis. As I recall, Professor Robert Turner saw this and said to himself, "*Pah*! It's just an artifact." and returned to his office. There, though, he picked up Cho's 7T atlas [3], which shows MRI images with corresponding cadaver slices. The stripes were visible on Cho's images, and Bob became a believer. I had gained my first CC-stripes disciple!

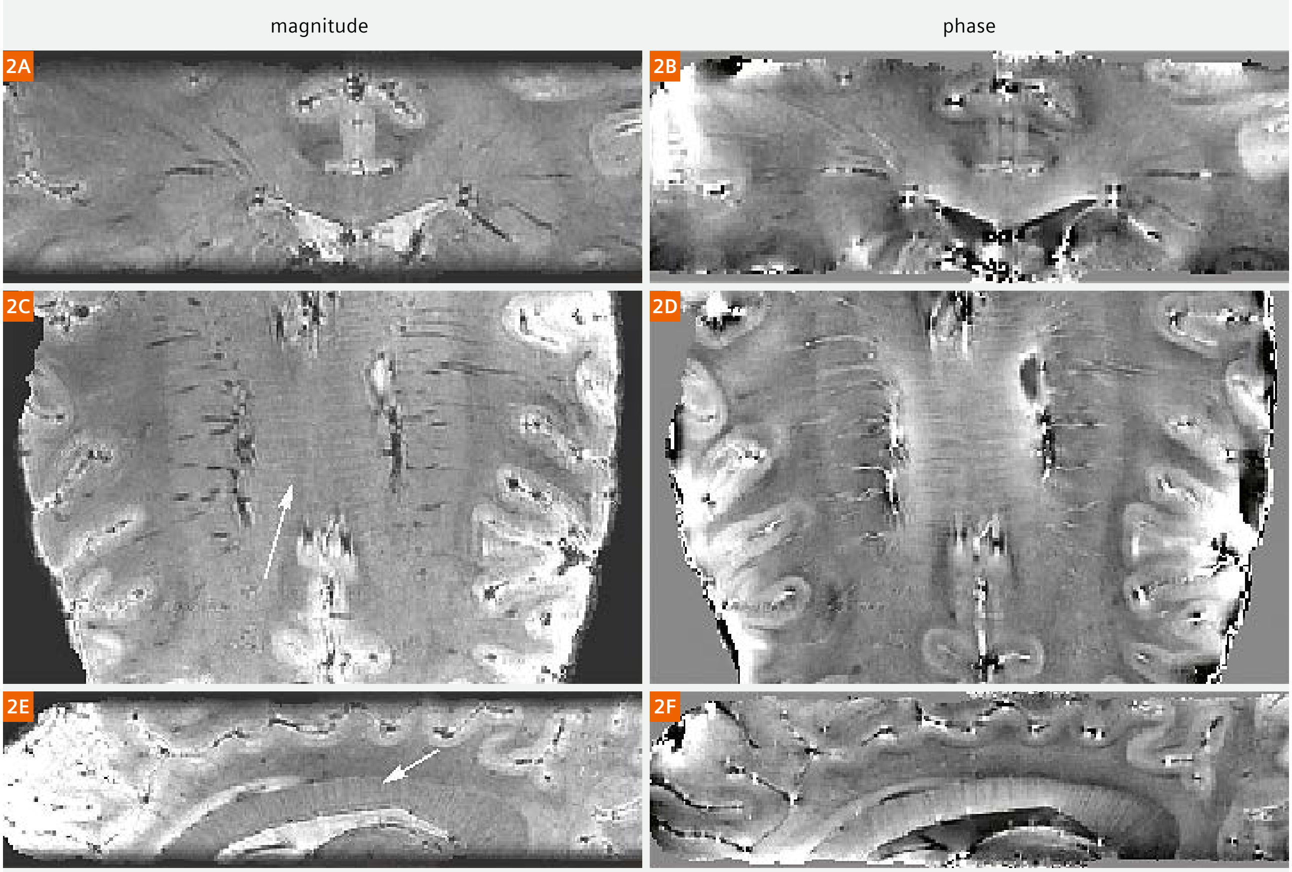

Figure 2:
3D GRE shows the stripes in the corpus callosum in both magnitude and phase images.

Like any true disciple, Bob began spreading the word. He started a collaboration and asked the members of his team to look into these stripes. Soon we had better images, with 3D GRE images with 0.5 mm isotropic resolution showing the stripes in orthogonal planes (Fig. 2). Such a pattern can only be explained by a 2D plane, rather than a linear structure, so that eliminated the suggestion that the stripes were purely vasculature. Additionally, an examination of the *second* eigenvector of DTI datasets showed a very similar radial pattern. Bob found literature from prenatal brains [4, 5] showing that septa exist in early brain development in just the sort of pattern we were seeing, but then seem to vanish around the time of birth. Another CBS researcher pointed us to Klingler's photographic atlas [6]. Klingler's preparation of brain samples involved fixation, freezing, and thawing, and then exposing the fiber bundles by gently removing tissue. The CC in the atlas clearly has a ribbon-like or foliate appearance. Since this is a *photographic* atlas, we could now counter the argument that the drawn atlases were not a true representation of anatomy (Fig. 3).

However, judging from the Editors remarks to our first submission, much more evidence was required. I began trying to find out how often this structure appeared in published anatomical atlases. Searching for this was fairly easy – there are many digitalized anatomical atlases available online, and one can spend many happy hours perusing them. The pictures are often very beautiful in their own right. I set myself a target of finding the oldest representation of the stripes, and ended up with a selection that included Gray [2], Dejerine [7], Bell [8], and Vicq d'Azyr [9].

This allowed me to show that the CC has been represented with these radial stripes for over 200 years (Fig. 4). I could therefore say that UHF MRI can now show *in vivo* something that for two centuries had only been available from *ex vivo* preparations – and indeed largely forgotten about.

Armed with numerous representations and a more complete analysis of the data, our paper entitled "After over 200 years, 7T magnetic resonance imaging reveals the foliate structure of the human corpus callosum *in vivo*" was accepted by the *British Journal of Radiology* in March 2017 [10].

So why use UHF MRI? Well, my experience shows that it allows you to see things that you really cannot see otherwise – not with lower field MRI, not with CT, not with PET, and perhaps most importantly, not without cutting the subject open!

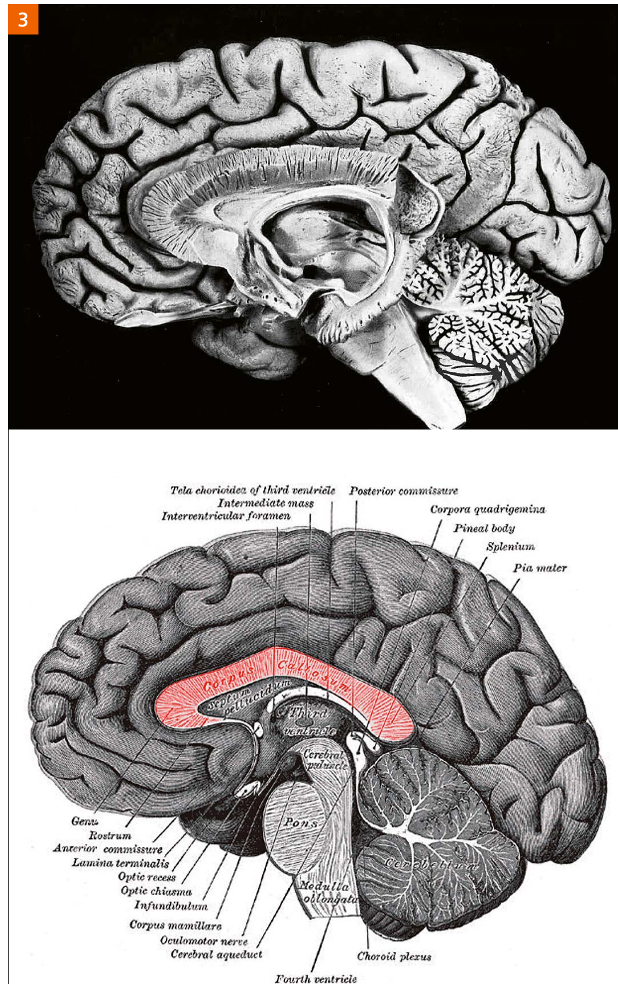

Figure 3:
Confirmation of the ribbon-like structure is clearly visible in Klingler's photographic atlas (top), which verifies that the stripes shown in the *Gray's Anatomy* diagram (bottom) are based on real observation rather than artistic license.

Acknowledgements

This journey from artifact to anatomy would not have been possible without the help of Alexandre Vignaud, Andreas Kleinschmidt, Denis Le Bihan, Robert Turner, Andreas Schaefer, Bibek Dhital, Alfred Anwander, and many others.

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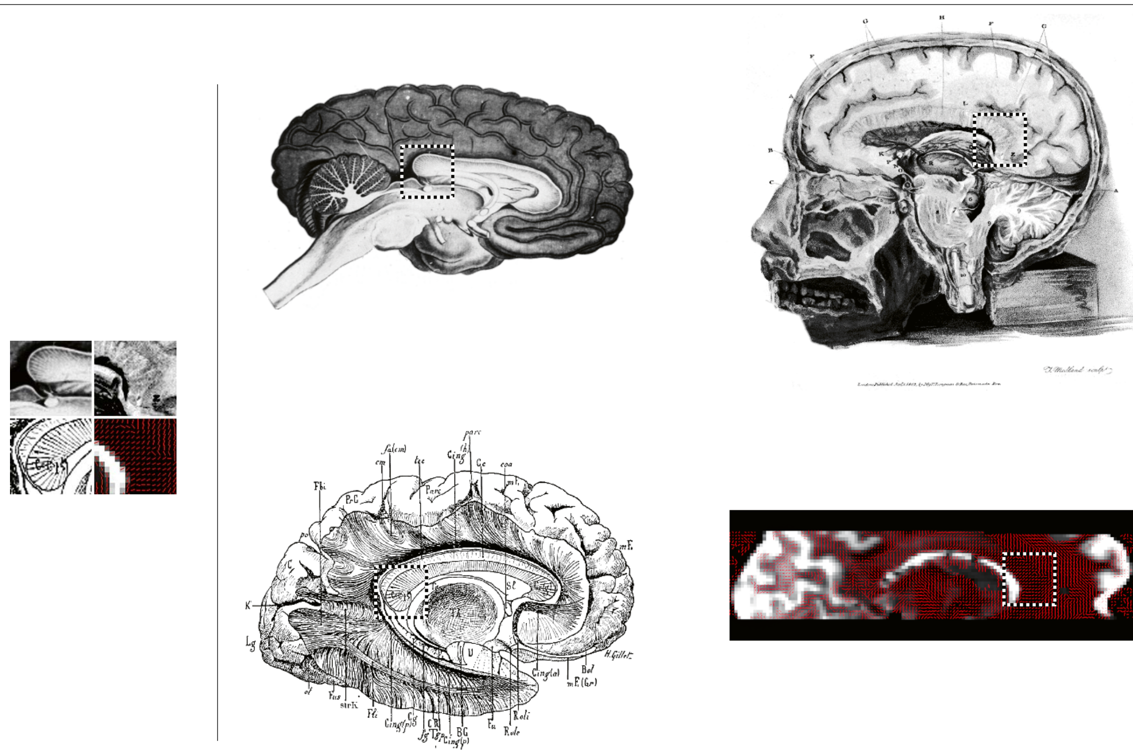

Figure 4:
Further confirmation can be seen in the atlases by Vicq d'Azyr (1786, top left), Bell (1802, top right), and Dejerine (1895, bottom left), as well as from the *second* eigenvector of DTI data (bottom right).

References

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