RF coils for high resolution imaging of the human visual cortex at ultra-high fields

7
Valorisation

Knowledge Valorisation

Knowledge valorisation refers to "the process of creating value from knowledge, by making knowledge suitable and/or available for social (and/or economic) use and by making knowledge suitable for translation into competitive products, services, processes and new commercial activities" - as detailed in "*Regulations governing the attainment of doctoral degree*", §22, Maastricht University.

Within this thesis, I presented fundamental applied research in the field of RF engineering with direct applications for enabling cognitive neuroscience research. In particular, I used innovative RF receive and transmit coil layout methods to design and validate RF coils for both *in-vivo* (Chapter 2) and *ex-vivo* (Chapters 3-5) use, at UHF strengths of 7T and 9.4T respectively. These developed coils, therefore, are not only relevant for researchers employing MR methods to study brain structure, function and connectivity, but also for those utilizing ex-vivo imaging methods such as Diffusion Weighted (DWI) and Susceptibility Weighted Imaging (SWI) to further probe and understand the neuronal basis of connectivity in the human brain. Over the course of my work at FPN/CN, researchers have stressed upon the need for customised RF coil hardware for their high-resolution imaging needs, and the work detailed in this thesis describes the development of such coils.

7T: From research flagship to clinical trendsetter

MRI is a non-invasive imaging method that has established itself as an invaluable imaging modality for both clinical and research purposes. While field strengths of 1.5T and 3T are the norm in a clinical setting, a lot of cognitive neuroscience research focuses on imaging at 7T [11, 14]. Recent policy updates (as of October 2017) have cleared the way for the clinical use of 7T scanners (Siemens Magnetom "Terra") through

FDA (US Food and Drug Administration) and CE (Conformité Européenne) approvals. The gains afforded at these higher field strengths include more than twice as much SNR per unit time, resulting in higher spatial resolutions and decreased scanning times - thereby enhancing clinical acquisitions and potentially reducing patient discomfort and time spent for an examination. Evidence on the benefits of high-field imaging for clinical purposes has been published by Zwanenburg et al. [13], Van der Kolk et al [16] and Trattnig et al [160], among others. With the increased Signal-to-Noise and Contast-to-Noise ratios afforded through 7T imaging, pathologies such as multiple sclerosis (MS), brain tumours and cerebrovascular diseases can be easily identified. With the achievable spatial resolution at 7T MRI approaching the scale of pathologies involved in neurodegenerative diseases such as Alzheimer's (AD) and Huntington's diseases (HD), further insight into these afflictions can be gleaned [161]. The ability to garner additional pathophysiological information can result in quicker diagnosis and start of treatment, while also providing insight on the development of new treatments for said diseases.

In this context, the availability of customised RF hardware is of primary importance when it comes to imaging specific anatomies, such that the gains afforded at high field strengths can be effectively harnessed by the researcher and/or clinician. For instance, the RF head coil detailed in Chapter 2 can not only be used for conducting high-resolution, visual fMRI experiments, but can also help in diagnosing, for example, cortical blindness [162, 163] and occipital infarctions [164] in prospective patients. The same RF coil design can also be easily adapted to image other brain regions, such as the auditory and frontal lobes, while further modifications to similar coil geometries can help enhance clinical imaging at lower field strengths ($\leq$ 3T). With wide-scale clinical adoption of 7T systems on the horizon, novel RF receive and transmit coil designs such as that outlined in Chapter 2 of this thesis will play a crucial role in enabling high resolution, high throughput clinical datasets.

Neuroanatomy and histological imaging at UHF

Diffusion magnetic resonance (dMRI) is a non-invasive imaging modality used to probe the connectivity and microstructure of the human brain, both through in-vivo and ex-vivo acquisition methods. A limiting factor for in-vivo dMRI is the average voxel size, which ranges between 1-3 mm, and for ex-vivo dMRI the same voxel size can be in the order of a few hundred micrometers [165].

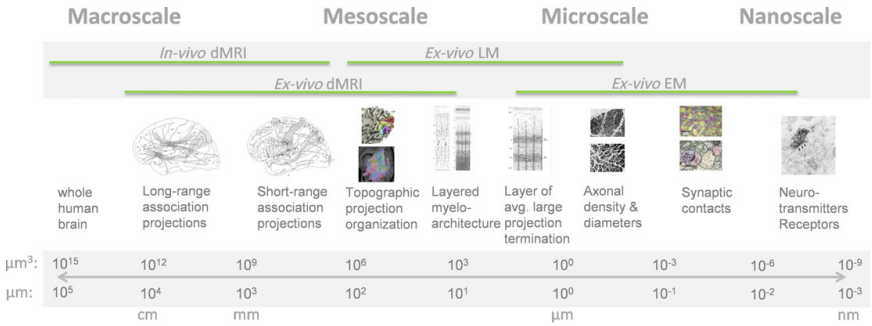

Figure 7.1: The multiscale nature of human structural brain connectivity and its measurement with different techniques. The measurement of the connectivity phenomena here refers to features directly resolved by the acquired spatial resolution of the technique (not by modeling the contrast over multiple measurements and indirectly inferring statistics of such features, as in microstructure modeling of diffusion MRI). dMRI, diffusion MRI; EM, electron microscopy; LM, light microscopy (Reproduced with permission from Roebroeck et al [165])

In-vivo dMRI has had a crucial role in mapping human macroscale connectomics, as evidenced through the Human Connectome Project [166] in which macroscopic human brain circuits have been mapped with in-vivo dMRI and tractography, along with fMRI measurements, across a large population of healthy adults, in order to create a " connectivity map" of the human brain and its various connections across cortices. At the other end of the spectrum, as shown in Figure 7.1, light microscopy (LM) techniques have helped study micro and nanoscale connectomics on small tissue samples.

Ex-vivo dMRI plays an important part here. With its ability to achieve very high spatial resolutions (hundreds of μm's) across FoVs larger than those possible with LM, it represents an ideal method for mapping mesoscale connectivity. At the same time, the connectivity and tractography maps generated from the high-resolution ex-vivo dMRI datasets need to be validated using histological techniques on the imaged sample, such that the different processing techniques implemented can be carefully evaluated and compared. In this regard, it is extremely important to not only have access to high-field MRI scanners fitted with strong gradients, but also to specific RF coil hardware relevant to the geometry of the sample being imaged. As detailed in Chapters 3-5, close-fitting, conformal phased array coil geometries provide extended coverage of the entire sample and the small-diameter coil elements enable high SNR near the coil surface (and by extension in the gray matter of the tissue under investigation, as the cortical layer is closest to the coil elements). We were able to achieve datasets with resolutions of upto 60μm isotropic for ex-vivo anatomical images and upto 200μm for quantitative acquisitions for relatively large tissue samples (upto 1 cm thick). The tractography results garnered from these datasets can then be validated by performing LM histological analysis on the same tissue sample, providing researchers with a robust, ground-truth measurement when comparing approaches to diffusion modelling.

Only a handful of research centers have access to a 9.4T human scanner, while many others have access to 7T human and 9.4T narrow-bore, pre-clinical (or animal) scanners. The work detailed in this thesis can be easily adapted to function across a variety of scanner configurations, thereby providing researchers with a solid RF platform for their high-resolution imaging needs.