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Ultra-High Field MRI Technologies: Physics-Based Innovations for Early Disease Detection

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Annotation: Ultra-high field (UHF) imaging systems with magnetic field strength ranging from 7-10.5 tesla (T) are now commercially available for preclinical and clinical applications. UHF magnetic resonance (MR) imaging is an emerging technology, especially of certain pathologies routinely overlooked by lower-field strength magnetic resonance systems, which would benefit from high SNR. However, the UHF transmission field in the region of the imaged anatomy is an important challenge to be addressed as increasing B0 intensities increase B1+ inhomogeneities affecting the accuracy of spin-state excitation and nullling, as well as generating local overheating. On the other hand, acquisition of the same anatomical region with UHF imagers is a challenging task since high field systems shorten T1 and T2 relaxation times. Thus, absolute quantitative measurements with UHF systems would require the implementation of correction techniques or special sequences possibly available in the proprietary sequence library, but not readily available in clinical settings. Signal-to-noise ratio increases with 7T scanners, and further, hitherto unavailable or too costly spatial resolution is attainable in conjunction with ultrafast acquisition techniques (UFT) at a motion-sensitivity similar to that of lower field strength systems. However, patient outcome will depend on a new evaluation process currently not available on the market. Highly negative non-chemically shift referenced water-only fat suppression techniques in combination with special B1 shimming methods, either via dedicated phantom or a combination of B0 and B1 field maps are urgently needed. Development of fast radiofrequency (RF) spoiling techniques on higher field platforms similar to those regularly used at lower field strength, RF coil alternatives, and parallel transmit support will be also required. Implementing water relocatable sequences and compatibility solutions with current clinical settings promises yet unqualified but predictable outcomes.

1. Introduction to Ultra-High Field MRI

Magnetic resonance imaging (MRI) is a non-invasive, medical imaging modality used for clinical diagnosis, evaluation of treatment of disease in tissues of the human body. Decades of research in systems and sequences of MRI, has led to its use in visualizing different nuclei at unimaginable detail. Increasing the magnet field strength has always been the driving force for improving the capabilities of MRI since the signal-to-noise-ratio (SNR) scales approximately linearly or even higher with the field strength. To this end, the first magnet systems with 9.4 T for human imaging have been installed in research centers around the world in 2016. Large public medical centers have vested interest in this enabling research tool for disease detection. A number of understandable concerns plague this extremely high field potential of imaging: increased RF power deposition with respect to whole-body SAR regulations, potential malfunctioning of devices, increased risk of incidental findings, and public misperception of the deep field imaging technology [1]. Motion during scans leads to image artifacts in a number of imaging modalities including MRI (static contrast imaging in this case). In the ultra-high field (UHF), e.g., 7 T MRI and above exhaustive techniques are in place work in progress with mixed success to alleviate these motion artifacts. Health regulatory bodies and institutions side with caution in allowing UHF whole-body imaging: screening purpose is yet without direct oncological relevant information. On the other hand, while UHF has been 10 years mostly brain-centric, there is a growing interest and momentum in the parallel development of body and musculoskeletal MRI [2]. Healthy and diseased small joints can be e.g. 1. 2 11 suffer from surrounding position and rotary motion in the improved visibility, and highlighting mostly cartilage structures requires high resolution long TR imaging (3D). It is non-trivial to have such cubic whitematter accuracy at nominal 7 and 4 mm-RF resolution at the lower 3 T with rapidly multiple coil setup and stripping local placement exclude random-angle-filling of live/moving subjects at short setups. In the general imaging alloys, hybridized networks and lumped-to-distributed-wave transition are a surefire methodology for continuous B1-field intensity symmetricity enhancement and hardly achieve tens of MHz utility.

2. Fundamental Physics of MRI

Magnetic resonance imaging (MRI) is a well-established and highly successful technique for acquiring in-depth images of the human body in vivo. It is non-invasive, ionizing radiation-free, sensitive to soft tissues and fluids, and has straightforward multi-contrast capabilities. Once thought to be limited solely to the realm of biochemistry, MR is now firmly entrenched in medical applications. Due to these unique advantages, MRI has become the greatest success story in clinical imaging and is now regarded as an essential technology in any hospital imaging department. However, there remains great potential for technological advances, which RF coil design could help facilitate. However, the design of RF coils is difficult because of the intricate bioelectromagnetic physics involved. A review of the basic physics of MRI is therefore warranted and would aid in educating and training entry-level engineering imaging professionals from diverse backgrounds.

The physics of MRI is well documented and is often taught as part of MBA programs in healthcare management, electrical engineering, physics, biomedical engineering, and medical imaging. Educational modules are readily available in a variety of formats, including graduate courses, online or in-person dialogues, and written materials. Usually, simple undergraduate mathematics is employed to derive and explain the main imaging mechanisms, which includes biology, RF, magnetic resonance, RF coil design, image formation, imaging controls, and image processing. Many books, presentations, and references are devoted to the physics of MRI.

MRI is based on many deep physics concepts, such as nuclear magnetism, resonance, gyromagnetic frequency, Larmor precession, spin coherence, phase coherence, relaxation, diffusion, MRI contrast, B0 inhomogeneity, B1 inhomogeneity, and their effects on image quality. These physics concepts can also be explained with ingenious analogies and illustrations. For a deeper understanding of the physics of MRI, classic textbooks in advanced electromagnetic theory, quantum mechanics, statistical thermodynamics, communication engineering, and radio astronomy can also be consulted. Exploration of these deeper topics is advantageous for devising new diagnostic imaging approaches as technology continues to develop. [3][4][5]

2.1. Basic Principles of Magnetic Resonance

The majority of our body is water and hydrogen atoms are randomly oriented nuclei in that water. The function of the magnetic resonance imager is to detect the magnetic resonance signal of those hydrogen nuclei. The MRI data are used to reconstruct spatial distributions of those nuclei by an image reconstruction algorithm. Whether patients can benefit from MRI, and how much benefit they can receive, depends on how sensitive the detection of MRI signal is. Hence a better understanding of the basics of MRI technologies will help locate poorly-investigated MRI signal sources and improve image quality of the sources.

Magnetic resonance imaging was invented primarily to image hydrogen-containing tissues non-invasively, and is now well-established as the most sensitive imaging modality for soft tissues with widespread clinical use. Over 30 years, MRI technology has advanced a great deal. Exploiting other nuclei than hydrogen for MRI is attractive for gaining more diagnostic information. For instance, fluorine containing substances could be used for studying tissue perfusion. However, current fluorine MRI techniques remains experimental. The major problem is that standard MRI systems are not designed to handle materials other than hydrogen. Furthermore, fundamental differences in both physical and diametrical properties between the hydrogen and other nuclei makes it challenging to make an imaging system switching mode between hydrogen and those nuclei. [6][7][8]

2.2. Signal Generation and Detection

The field of ultra-high field MRI is still in its early days. Several groups have made inroads producing convincing imaging results, scientists are only beginning to explore and exploit the unique capabilities offered by these ultra-high field magnets. Early explorations were largely limited to widely available coils currently in use. With the rapid growth in UHF MRI activity over the past years, a whole host of technologies have been adapted or developed with the close coupling of, and concerted focus on the developments in RF coil manufacturing and design.

Several frontline RF coil technologies with detailed discussions of their anatomical region as well as some unique challenges in the manufacturing and deployment of these UHF MRI coils, techniques, and approaches developed to combat these problems have been developed. These range from the more traditional reception-only 32 channel coils, to the more modern network designs, through to the more exotic split ring resonance technology and a number of techniques developed to enhance their performance. Beyond reception-only coil designs, parallel imaging has become an active area of focus for horizon-high field technology development, focusing on parallel transmit technologies for whole body scanners, parallel transmit systems with restricted field-of-view capabilities for dedicated brain systems and installation of alternative amplifier technologies to provide this crucial level of freedom. Control of the transmit field has also been closely coupled with mapping methodologies developed for use with any of the array and discrete coil systems described, that have endured the same paradigm shift. Standard techniques such as phase mapping at lower fields have been adapted for use yielding improved results, while newer, faster pulse-acquire and voxel-based imaging acquisitions have been made possible due to recent UHF MRI developments in hard- and software. Parallel imaging reconstruction techniques originally developed for signal acquisition also translate easily to this new field. The limited experience with the design and adaptation of dedicated test strategies focused on system health monitoring specifically could be seen as caution for deployment, however systems designed to meet standards exceeding those currently present will yield coil systems with high levels of reliability. Due to the relatively few RF coil systems available to UHF MRI as a whole, much of the coil- and experience base is cross generational between OEMs and research institutions leading to possible delays in knowledge transfer and expansions of expertise, however this cannot be seen as a barrier to developing systems of high performance. [9][10][11]

2.3. Contrast Mechanisms in MRI

Inspired by the improved signals in the ultra-high-field MRI systems relative to the clinical MRI systems, more and more efforts have been devoted to better signal detection for earlier diseases diagnosis, which contributes to the grant funding on developing novel physics-based contrast mechanisms, including T1 contrast mechanism, T2 contrast mechanism, and others. Since the discovery of magnetic resonance phenomenon in the 1940s, the successful application of magnetic resonance imaging in clinical medicine has been mainly based on the water resonance of free water content in human bodies, where health conditions are diagnosed by revealing the tissue structure difference utilizing the different proton spin states and resonance frequency shifts in the presence of external magnetic field. Although significant advances were achieved, water T1 contrast mechanisms are still limited by scanning duration or T1 relaxation time, which hampers the routine usage of timely diagnosis in early-stage diseases, such as small-size stroke and small-size prostate cancer. In the 1980s, the surface-bound water, where water protons are influenced by macromolecular components in tissue structure, was indicated to have an extremely longer T1-spin echo TI matrix due to its modulated chemical shift and magnetization effect. However, interfacial water protons have not been utilized in any MRI despite their much longer free T1, because it was technically too difficult to detect such signals since either the sampling-related scattering signals or the large frequency shift bias.

In the 2020s, an innovative solid-contact probe with the design of impedance boundaries was developed, giving rise to the enhanced sensitivity for sub-silicon mm-sized solid contact. Such time-gated semi-analytical model with finite element method was established to reveal the signal enhancement principles and mechanisms by a comprehensive insight in the signal generation process. Then, the enhancement effects and mechanisms were experimentally validated at ultra-high field MRI system with a lithium tantalate crystal as ultra-high-frequency solid contact. Based on such advancements, a series of T1-derived biological or pathological interfaces, including the self-assembling peptide hydrogel-glutamate receptor, amino-acid/-protein’s coaxial hollow capsule or liquid droplet; and tumor-specific activation of glutamic dehydrogenases in an “aqueous-to-solid” phase transition, were explored. These pioneering works, which uniformly leverage the remarkable differences in local T1, spin density, and magnetic susceptibility between probes and backgrounds, enables the quantitation or contrast of a varied range of biomarkers with ms-sensitivity. In this manner, remarkable sensitivity, specificity, and non-invasiveness can be achieved for precision medical imaging, which is Hermian.

3. Advancements in Ultra-High Field MRI Technology

There are important technology advancements in Ultra-High Field MRI systems for brain imaging. Those innovations relate to MRI systems' hardware and software solutions. Altogether, those multi-faceted developments in UHF-MRI technologies provide new possibilities to study the human brain in vivo. Importantly devoted efforts to the native field strengths matching anatomical features of the human brain would unfold this technology for clinically relevant brain mapping.

Technological and scientific advancement goes hand in hand. Central to the progress of MRI technologies are magnet development, magnet handling, scanner software, and data acquisition software. Continued effort in improving those aspects of MRI technology will enable broader application of UHF-MRI systems in biomedical researches, including in-vivo studies in MRI cellular imaging, biomolecular MR-spectroscopy, and functional connectivity of brain networks [12].

Continually innovative efforts in coil/PACS technology would benefit spectral imaging and data acquisition speed, and they would serve many applications. One important area of application is investigation of the metabolic disorders in the aging brain, alzheimer's fields. Important spectral measures, e.g., choline, creatine, and N-acetylaspartate, had been reported that relate to active/inactive brain tissues. Multi-channel LCMR coil with iGRAPPA access to both the low and the high-field region of k-space is one possible solution to meet the spectroscopic demand, allowing simultaneous CR and PRE images acquisition. The coil/PACS technologies development would also enable detection of injected cellular imaging probes in a systematic manner [2]. The new possibilities open single voxel coil and other spectral detection based applications at UHF regime and studies on MR-signal modelling and coil transmission could be conducted using the new technologies. A high spectral SNR is also key for probing nanomolar spectral reporters like paracetamol-HCl. Development of water and fat excitation dB0 insensitive spectral selective RF pulse will be useful for many important applications regarding cardiovascular, tumor study, and metabolic, and probing novel imaging and contrast agents.

3.1. Magnet Design and Engineering

Several low-field 'landmark' 0.5, 1.5, 2.0, 3.0 Tesla whole-body MRI systems were installed in clinical and research environments during the 1980s-1990s to provide reliable MR images of human brain, joints, abdomen, and thorax. The increasing interest and investment in high-field clinical trials, brain research, and drug safety in the early 2000s shifted the focus to ultra-high-field ≥7 T, predominantly static field, MR systems during the 2004-2022 period. Such systems offered remarkable human and pre-clinical brain images, to measure and monitor small anatomical structures, concentrations of patho-physiological, metabolite, and compatible pharmaceuticals down to 1 mm3 and 100 nM. The initial understanding and values of 4-6 T systems had been intensified over 10-15 years but unfortunately lost at investment and funding stages. A smoother evolution of 30-50 years was anticipated for systems >7 T. Even a superior temporal spatial resolution was inevitable with more intense fields and lower input thermal noise with better SNR of voltage signals. However, despite unique in-vivo metabolite detection achievements, a down-scaling event with slow commercial technologies was more likely than an early bench-marking event.

It is desired to be embedded in a mechanically and thermally stable magnet. It is also desired to provide an easily controlled variable field. Although horizontal configuration is necessary for higher field undulator, recent magnet configurations, specifically vertical gradient configured short magnet, are too attractive for selected applications. The expert also calibrated to higher field exact spectrometers with large bore available with strong dispersion and improved mass resolutions of 1.2 M possible. Ultra-high field NMR spectrographs with 1.0 mm3, ≤300 nM detection were developed to more broadly apply to materials, chemistry and clinical diagnostics. Thus, superconducting magnets were selected to implement, innovated by the axisymmetric magnet for 3D field and product harmonics with layout, of 1.5 m ID, 7.0 m OB, ≤18.0 T, core segments with iron yokes modules and very low thermal conducting shielding set in liquid He Dewart.

3.2. Radiofrequency Coil Developments

Despite the apparent advantages of UHF MRI, a number of physics-based challenges and requirements remain to be solved. Due to increased RF field inhomogeneity at UHF, improved RF coil technology is the first and vital step. MR spectroscopic studies of Ultra High Field (UHF) MRI consider several radiofrequency coil requirements: Advances in RF receive coils include investigations of reflector coils, and RF design with tighter tolerances for higher center frequencies, and an increase of total number of coil elements in receive coil array designs; Improvements in RF transmit coils deal with array designs with more resonator elements, new coil types such as dipole and vintage coils, and the feasibility of parallel transmission (pTX) methods. The primary goal is to provide transmit field B1+ homogeneity and distortion-free excitation pulse/system performance over a target area of interest in the brain. Various investigations of pTX coil design configurations for initial use in 7-Tesla and 9.4-Tesla head and cervical investigations appear promising. RF safety is a major concern for successfully implementing UHF MRI in clinics; the RF Specific Absorption Rate (SAR) study is necessary to improve patient compliance and safety.

At lower magnetic field strengths, bifilar-wound quadrature RF coil designs have been very popular in dedicated animal magnetic resonance imaging scanners; Parallel RF coil arrays have been developed to satisfy the performance requirements of 3Tesla MRI systems. However, the recent need for use of dedicated RF coil technologies for 7Tesla human MRI and development of novel coil technologies for non-linear transmission, improved decoupling, and improved penetration have spurred an upswing in new shape RF coil technologies. New exciting designs include better coupling coefficient cylinder solenoid coils, robust globally-decoupled RF coil arrays, self-shielded RF coils and multi-channel RF coils. Integrating with modern simulation methods and imaging hardware, both experimental and simulation-based approaches have been used for the modeling of RF electric field and magnetic field distributions during the RF coil design phase while experimental-only measurements are used to estimate normal B0 field inhomogeneities for designing susceptible RF coil shapes [1] [13].

3.3. Gradient System Innovations

Magnetic Resonance Imaging (MRI) continues to be one of the fastest growing imaging modalities due to its enhance conceiving ability of images utilizing non-ionized radiation. Quantitative studies of the physiological information and/or functional imaging are useful to achieve a previous diagnosis and early detection of disease. These techniques, however, require high field strengths because the information of interest is in the low MR signal follower. Therefore, early prior researches have shown a considerable contest about the availability of ultra-high field MR system to achieve these techniques over clinical 1.5 T or 3 T MR systems under physical laws [14]. Hardware configurations such as the magnet, gradient, RF, etc. are in fact desired for such a powerful system. Nevertheless, most of the focus are on the designs and/or development of the magnet in a physical space. It is urgent to integrate all the other subsystems in despite of impossibility to be preceded worst case plans. Even after a mindset for feasibility of integration is assured, this might need a mutual consideration between a physical shape of hardware and availability of the imaging sequences as well as the post-processing algorithms. Hence, this portion of the requirement covers general topic of hardware integration in a system level (first generation) and development of a modicum platform in a machine level but hardly on all the fine structures in a more detail (second generation).

4. Image Acquisition Techniques

Image acquisition techniques comprise two general areas: 1) RF pulse sequence design techniques, and 2) reconstruction and display of images constructed from the acquired k-space data. The focus here is on pulse sequence design techniques which improve image quality and speed. This includes more systematic and informed means of designing and implementing RF sequences as evidenced by the exploitations of parallel RF array coils with new specialized RF pulse design and transmit methods. This also includes explorations of prospective acceleration methods to speed up image acquisition which have received particular interest with the advent of ultra-high field (UHF) human scanners. At these higher fields, scan time is often limited with some techniques less robust and more susceptible to artifacts. Consequently, increased scan times can lead to increased signal loss due to T2* decay both uniformly and spatially in the case of B0 inhomogeneity. Despite these challenges, pulse sequence innovation remains a top priority for potential UHF clinical success as it is largely with new pulse sequences that the improved imagery and contrast are obtained, particularly for fMRI.

An MRI study provides a means of implementing a pulse sequence design technique for the specialized pulse shapes found in the 90-degree excitation of arterial spin-labeled (ASL) sequences as well as other RF pulses in these applications. This is accomplished via a coding technique by which a set of optimization techniques and tools communicate with each other and with vendors' pulse sequence programming environments to effect pulse sequence design. Aspects of the resulting approach are detailed with special emphasis on interfaces and tools that greatly facilitate wider dissemination of the coding and assist teaching. The development of the APTOnce and EPI-EPI RF pulse sequence design packages for both the Siemens and GE product lines of MR consoles is discussed. These packages provide tools that grant access to vendor proprietary C++ compilers and run-time executables that can be run on a workstation or other platforms to optimize pulse shapes produced and used in widely implemented ASL and EPI. This widespread accessibility makes design of RF pulses to produce more robust and improved imagery much easier and is a step toward improving the clinical impact of MRI in prospective disease detection [15].

4.1. Fast Imaging Methods

Neuro-chemical distributions can be measured and visualized noninvasively in the brains of humans and animal models using magnetic resonance spectroscopic imaging (MRSI). MRSI is a powerful technique, due to the capabilities of ultra-high field MR scanners ($\geq$7 T) that improve the signal-to-noise ratio (SNR) and chemical shift dispersion. MRSI at ultra-high fields, however, presents data acquisition challenges, including long acquisition times and contamination of the MRSI signal.

To mitigate the effect of the long scan time, inexpensive low-SNR-denying post-processing algorithms have been employed. B1 inhomogeneity may be reduced with optimization techniques to ensure magnetic homogeneity. Artifacts from lipid contamination are difficult to correct with post-processing based techniques; therefore, faster MRSI acquisitions producing MRSI signals predominantly in the free induction decay (FID) are preferred to reduce scan times and improve the SNR. Conventional MRSI takes advantage of the spectral echo in the presence of spatially selective pulses to image the metabolite signal using an echo-planar readout (EPSI). Uncorrected ghosting artefacts, which manifest as discontinuities in the spectrum and amplitude of metabolite signals, may arise from the entrance of zero gradient fields during spatially selective excitation. On the other hand, nonphase encoding (multi-band methods) methods, which acquire a FID in the presence of radiofrequency (RF) pulse width modulation, allow for a low-ghosting chance. The method is, however, limited by the number of frequencies that can be simultaneously transmitted without wavefront distortion.

To reduce the scan time, lipid signal suppression techniques are preferred due to the high concentrations of lipids in the skull containing compact and frequency-dispersed spectral dispersivity. Inner volume selection (IVS) methods, such as slice or slab selection methods, localize the spin-echo signal to the volume of interest and omit the signals from surrounding tissues. Unfortunately, IVS methods suffer from reduced spatial coverage and thus reduced anatomy, long echo time (TE), long repetition time (TR), and on-resonance saturation of the lipid signals. Nonspatially selective methods, such as chemical shift selective fat saturation and spectral-selective inversion recovery, have been proposed to crush the lipid signals with additional hardware, like a crusher coil [16].

4.2. 3D Imaging Protocols

Spatial resolution of dMRI datasets is crucial for accurate fiber tractography, especially in complex fiber geometries at ultra-high-field. However, until now, practical high-resolution dMRI for ex vivo mouse brain architectures has remained elusive at 21.1 T. Fully 3D dMRI data acquired in a matter of several days aims to enable better understanding of mouse brain enameling and structural changes due to pathological scrutiny. Subject movement abrogates spatial fidelity between anatomical measurement, 3D representation, and functional measurement. However, recent advances and miniaturization of ultra-high-field MRI devices now enable high-resolution dMRI in living small animal models native environments. Spherical tube optical phantom has been embedded as a fixture to scanned vivo mouse heads, and rf-staged ventilation keep breath harshness within structural tolerances for accurate in-air and in-vivo measurements. Rapid developments of new coil designs and transmit-receive technologies are increasing the availability of parallel imaging in ultra-high-field MRI systems. As a noteworthy example, SMART, a novel, folding-statemible, transportable RF coil, has been developed for a variegated, robust, and flexible hybrid multimodal imaging platform capable of performing fully integrated MRI and multi-photon microscopy based experiments at exceptionally high-magnetic fields (ref: 205a6ca2-b43b-4da7-a9fd-3844be27b167).

As ultra-high-field mri tackles on deeper, higher-resolution, and higher-dimensional measurements of scrutinized samples, tuning for non-noisy, accurate, wide-field observations becomes exponentially difficult with more free variables and ill-defined necessary measurement conditions. Data-driven self-calibrations with optimally tuned hyperparameters could overcome for viability of analysis. Lower-dimensional pre-analyses and computational models, on the other hand, could directly invert from observed noisy images to sample metrics and render reformulated inverse measurement functionals for optimization, previous works involving wave functions to recapture compressed images, or orientational models for averaged observations. Current work reveals synthetic views from utmost down samples, unravel cellular morphologies from less than an electron diffraction most classical 2D field, or deblurring stochastic microscopes with iterative constraints from their Hartley transforms. Conclusion using advanced datasets with the stuck best condition of various observations have outperformed expertise parameter tuning concerning to data-driven optimization via learned adjustable machine heuristics or manually designed adjoint estimation could foregoing observation variable ratios.

4.3. Functional MRI at Ultra-High Fields

In Europe, 70% of the 7 T and greater MR scanners are also registered as clinical devices, and clinical use already has commenced with over 1000 patients scanned for analyses of epilepsy, neoplasia, multiple sclerosis and cardiovascular diseases [17]. Large scale clinical trials are expected within the next years. Susceptibility-based contrast will open up the possibility to resolve revealing information about morphological, physiological and pathophysiological processes of several diseases at 7 T and greater field strengths, in particular when layers become thinner and more directly involving the minimal invasive use of contrast agents, but also in multi-contrast use with transient water saturation.

The development of ultra-high field (UHF, ≥ 7 T) MRI scanners has provided new opportunities for functional MRI (fMRI) [18]. UHF MRI, with greater availability of magnets, better scanning methodologies and software approaches, is advancing the characterization of clinical conditions, reliable characterization of brain development, improved understanding of neurodegeneration, easy transfer of fMRI discoveries from rodents to larger mammals, and availability of mega and ultra mega scanners for over 14T preclinical systems. With new developments, major metabolic, structural, perfusion, and functional imaging can now be performed at UHF. UHF has potential for addressing unanswered questions both in basic research and in translational, clinical, and preclinical UHF neuroimaging investigations. UHF approaches in both fMRI and ASL perfusion imaging are maturing, as a result of interactions between researchers and clinicians over various venues at national and international conferences.

5. Data Processing and Reconstruction

Data processing and image reconstruction methods for MRI are two topics very much alike but not identical. On one side, image reconstruction applies least-square minimization techniques, where a model of the k-space encoding and possibly the signal equations is inverted. On the other, data processing refers to all other manipulations that are performed on the MRS signals after reconstruction into an image. The two categories overlap, as algorithms for denoising, inpainting or de-aliasing, for example, are typically applied to both k-space and image data. Significant advances have been made in MRI reconstruction and processing methods, focused primarily on computational models that facilitate both the temporal and spatial encoding of the acquired MR signal and on effective optimization routines for solving the reconstruction problem.

Traditionally, image reconstruction was performed via a nonparametric Fourier transform approach, but mathematical models that represent the physical principles involved in the MR acquisition process led to much more flexible and powerful methods. As a result, regularized model-based methods now predominate in many aspects of MRI [19]. Efforts have been directed towards smart optimization routines and the incorporation of a priori knowledge, e.g., to describe tissue exact spatial distributions or fat distributions.

The recent progress and availability of machine learning and AI, however, has ignited great interest in this field and MRI-related applications, from image acquisition to reconstruction, and post-processing [20]. Recently, some of the above-mentioned approaches were grouped together and termed deep learning. The combination of fast and highly undersampled data acquisition and convenience of the trained network allows rapid image reconstruction in parallel. Though new opportunities seem to arise every day, the dream of an unbiased and unambiguous recovery remains still very far away. Novel acquisition schemes and physics-inspired methods can offer viable solutions to mitigate the unavoidable artifacts arising from the ill-conditioning of the image reconstruction problem.

5.1. Advanced Image Reconstruction Algorithms

In this section, advanced concepts and technologies pertaining to imaging systems that exploit physics-based modeling approaches are reviewed. Electromagnetic wave theory, the physics of MR signal generation and theory of CT, and how they are used in modeling of 3D MRI or transient-state CT systems will be reviewed. The methods and techniques to derive the motion- and noise-compensated reconstructions of 2D and 3D images from the measurements acquired with such systems will also be considered.

Recently, there is significant research interest in physics-based or model-driven imaging systems. Such a system consists of an acquisition system that collects the sampling of the images in the domain defined by the physics of the imaging system and a reconstruction algorithm that takes the measurements to recover the images in the conventional pixel/voxel domain. The parametric imaging systems which manipulate the physics effects of the imaging modalities based on the desired applications and the physics knowledge have the added advantage that the design and implementation complication are greatly reduced, and they can often perform one-shot or single-acquisition imaging [20]. However, there are very few systems on the market that are based on physics understanding so far. This is largely due to the difficulty in developing the physics-based reconstruction algorithms for such measurement modalities. For physics-based imaging systems, maintaining a strict and realistic relationship between the measurements and images in the mathematics of the imaging systems is necessary. Such operations notably include 2D and 3D Fourier transforms and convolutions which are non-linear and non-trivial in terms of both reconstruction algorithm design and computational efficiency. For different imaging systems, the pixels or voxels are much larger than the calculations in the default noise-free implementation of the operations. Other reconstruction algorithms such as temporal reconstructions that model the motion of the acquiring process, receiver coil sensitivity effects, and quantization errors which exist are also important.

Model-based reconstruction methods are generally effective, with guaranteed reconstruction consistency, while also computationally expensive [21]. The speed is limited mainly by the number of iterations required for acceptable reconstruction fidelity, and this number generally grows as more complex regularization is incorporated. In parallel, it is likely that model-based methods would continue to improve speed on standard desktop computing systems through optimized parallelism. Despite their heavy modelling assumptions and lack of guaranteed reliability of the estimated solutions, data-driven reconstruction methods are increasingly popular. State-of-the-art performance has been shown on target imaging modalities/models using convolutive neural networks with a large volume of training data. These models are computationally inexpensive, running in a fraction of a second, but large quantities of training data are needed to bootstrap the modeling process. However, the acquisition or simulated data may differ from the assumptions on which the trained model relies.

5.2. Noise Reduction Techniques

Magnetic resonance imaging exhibits intrinsic redundancy across independent coils and repeated acquisitions but suffers from substantial additive noise affecting images after reconstruction. Previous attempts to separate signal and noise in reconstructed data relied on modeling the noise process, yielding results that were coherent within each image but produced unrealistic images when averaged. The above introduces a strategy that leverages the redundancy of the system before reconstruction to jointly denoise multi-channel raw-data. It binned individual multi-channel k-space into separate filters, treating the raw data associated with signal and noise at different frequencies, respectively. Applying the filter to the data, noise is largely suppressed.

But important signal information at the lowest frequency range is likely compromised as well. Most importantly, it only reduces the noise floor in intensity data of each pair of coils but fails to improve the noise floor of image intuitively. The noise covariance of images is totally retained after denoising k-space data, failing to account for the correlations across images from different coils. While any reduction of noise floor in k-space will push the noise floor of images lower, principled modeling of coil-wise noise covariance may disregard some important signal information. Thus many of the state-of-the-art denoising techniques widely in use by many scan protocols effectively leverage the coil diversity built into multi-channel MRI systems. These techniques are well characterized but a major criticism is the reliance on reconstruction-ing, thus signal models, for noise reduction. An innovative strategy for 2D detection of the coil-mode for self-consistent spectral denoising in pre-reconstruction k-space has been developed, augmenting traditional point-set denoising approaches to a more tractable and robust parametric wavelet framework.

The vast quantity and diverse modality of MRI, especially multi-coil, poses even greater challenges for reproducible denoising, and poses even greater opportunities to explore alternative data representations and novel generative network architectures. As such, straightforward application of incautious.

5.3. Quantitative MRI Approaches

The tremendous successes of MRI lie in its versatility, where different contrast mechanisms can be exploited to reveal a wealth of information on tissue microscopic and macroscopic features. However, these traditional approaches suffer from inherent limitations in objectivity, interpretability, and reproducibility. qMRI methods address these limitations by the introduction of physics-based post-processing schemes that map the raw signal intensities to biologically-relevant contrast mechanisms like T1, T2, T2*, PD, and D [22]. In this way, qMRI provide an objective and efficient way to represent the data, where numeric values of the tissue properties are being measured. The ensuing quantitative markers can then be utilized to probe both macro- and microscopic information while optimally utilizing the dynamic range of MRI contrast mechanisms. The use of widely-available tools has allowed the accumulation of large databases for BMD and ADC, and have delivered compelling differences in these markers between the diseased and healthy states. Compared with traditional radiomics approaches, the qMRI methods offer three main advantages. First, it allows for the quantification of alterations in relaxation time that might be visually invisible using standard qualitative techniques, yet are quantitatively measurable. Second, qMRI methods provide scalability in the sense that qMRI extracts reproducible values, and therefore the question of where to set the cut-off is moved from the realm of the clinician into the realm of biology, facilitating longitudinal studies of both the same and different individuals. Finally, in addition to providing approximations of their underlying distributions, qMRI techniques decompose the tissue property into its constituent components, representing a richer form of data representation. To date, and primarily in the context of brain research, qMRI is being used to measure a wide range of MR properties. While the great majority of qMRI applications focus on the white-matter content and its integrity, qMRI parameters reflecting the tissue microarchitecture are becoming widely used in studies aiming to elucidate the pathology, integrity, and biodistribution of tumors and their infiltrative pattern.

6. Clinical Applications of Ultra-High Field MRI

Recent years have seen the emergence of clinical studies involving ultra-high-field (7-T) MRI. Several institutions have performed extensive experimental work using 7-T devices. Input from initial clinical experts results in awareness of safety considerations in 7-T MRI at the clinical level. Generally good results show the feasibility and potential advantages of 7-T musculoskeletal imaging [23]. However, 7-T MRI will require continuing attention and development to identify what 7-T modalities are more beneficial in clinical practice. The first European Experience of in vivo Study of 23 Na. Before and after MS treatment the changes in functional sodium MRI are displayed. The regions of 71 discreet regions are evaluated with a spatial probability approach. Musculoskeletal MRI at parallel transmit and receive system. Myelinated axons are responsible for multiple functions. They conduct impulses faster than the unmyelinated counterparts, provide support to neurons, and store essential nutrients.

Demyelinating, dysmyelinating, and traumatic processes can result in aberrant myelin formation and loss of myelin sheets [2]. The integrity of myelin is tracked by new imaging agents that characterize physical properties of myelin sheaths and axon-myelin coupling. Medical imaging, enzyme histochemistry, and molecular biology are combined to study myelination and its role in health and disease. For instance, new MRI acquisitions exploit the behavior of mobile multi-component molecules in diseased brain. New contrast mechanisms and new imaging agents based on the design of molecules with probes specific for myelin are introduced. Recently developed ex vivo and in vivo imaging agents to track 23 Na are also presented. 7-T imaging at 23 Na is expected to revolutionize neuromuscular imaging accessing cellular level in brains and nerves and these cutting-edge technologies advance the understanding of myelination and its consequences.

6.1. Oncology: Tumor Detection and Characterization

The progression of solid tumors is associated with spatial and temporal variations in the underlying physiology and biochemistry. Such variations can occur even within a few millimeters, causing heterogeneity at the resolution limit of conventional imaging modalities, and necessitating multi-parametric imaging to characterize tumor stemness, cellular density and proliferation, oxygen consumption and diffusion, and matrix stiffness. Low-field magnetic resonance imaging (MRI) at 0.5-1.5 T has the advantage of being less sensitive to motion and has greater availability compared to ionizing oder PET modalities; however, low-field images suffer from partial volume effects at the edge of lesions where normal tissue meets tumor. A multi-parametric quantitative (Q) MRI protocol was then acquired at 1.5 T. For the in vivo trials, orthotopically in implanted tumor models. A whole-body coil and a four-channel surface coil array were used to collect RF signals at 24 channels, which were subsequently subjected to reconstruction and mapping of the apparent diffusion coefficient (D), diffusion-weighted (DW), T2, and Q2. On the micro and nano scale, the equal numbers of the Q-MRI maps were registered and non-linear filtered based on a mixture of Gaussian (MoG) graph model. Probabilistic points of interest were generated from clusters of pixels and implanted back to the re-obtained 3D space. Global/Regional microscopy/photophysical parameters of phosphors were models for the classification task and validated on the curves of the true positive rate against the false positive rate. Such parameters were explored using carefully constructed bifocal optical filtering to decouple temporal and spectral luminescence of phosphors at high throughput and high yield.

To differentiate tumor and stroma Reconstructed (pixel-wise) Q2 was normal/standardized such that the distribution of values follows Q2-protocol on nontumor tissue in steady conditions to derive lesion-specific Q2-filters. Multi-parametric matches were quantified by morphing Q2-filter output, assigning the intratumoral heterogeneity pix-elements to tumor/T-invading margin/T-investigating margin/normal. Quantified multi-parametric matches attesting convex multi-parameter hull were sufficient for definitive discrimination of tumor and stroma. Automated toolboxes for Q-MRI and Q-Marl return the quantitative/MRI-marled tomography maps of the specified tissue before and after the analysis are provided to facilitate clinical portability development [24].

6.2. Neurology: Brain Disorders and Imaging

Within five years, advances in neuroimaging technology and analysis promise to expand the window into human brain structure and function in health and disease. Expeditions into the mysteries of the brain are a slow process; advances in brain science typically progress at a glacial pace. Clinical applications in brain science are no exception. Except for workflow changes motivated by ever-improving computation and the wide-spread adoption of diffusion tensor imaging (DTI) to study white matter integrity, tools of the trade in neuroimaging remain largely static [25]. Cerebrospinal fluid, blood-oxygenation-level dependent, differentiation of active from inactive elements in the metabolic soup that engulfs and nourishes the brain after positive emission tomography (PET)—these probes of the brain's secretable underpinnings and affordances remain in regular use. For the most part, so too do array-based microscopic measures of cerebral blood flow involving similar limitations that offer limited measure of far less studied proteins. Indeed, both widespread problems of this measurement anatomy have been targeted as areas for future developments with brain-science ramifications. Additionally, MRI-based measures of both implicit phylogenetic crown and explicit phyllogenetic crown give insight into neurodegenerative brain diseases lacking efficacious treatments.

Developments in DTI and diffusion-based tractography have spurred new insight into normal aging, compensation, and network changes in disease states. DTI-based measures effuse image moderation of chronic partial or complete ligament hypertrophy resulting in adult-onset cervical spinal cord compression where close correlations exist with change in clinical examination based on subserving, application, and objective measures of motor and sensory change. Additionally, DTI measures based on eigenvalues and fractional anisotropy give insight into early changes in Williams syndrome where understanding of the syndrome has heavily relied on neuroanatomical work. That most neurodegenerative brain diseases remain without treatments that ameliorate progression, and for that matter, cure such diseases, is regrettable given the predilection of some of these diseases to afflict targeting nodes in networks. Given the inherent complexities, development of efficacious treatments for neurological diseases poses a monumental challenge.

6.3. Cardiology: Heart Imaging Innovations

As one of the most clinically relevant applications of MRI, cardiac magnetic resonance imaging (CMR) is fast moving from a research technology to a routine clinical tool. In parallel with advances in field strength and the development of pulse sequences, a major advance is the design of cardiac dedicated RF coils that take fully advantage of the increased signal-to-noise ratio and parallel imaging capability at ultra-high-field magnets ([26]). With proper surgical planning and careful adjustment of the magnet room and body coil, routine cardiac imaging at the 7 Tesla is not only achievable but also clinically operable in today's standards for clinical and research purposes.

With higher field strength for the ultra-high-field cardiac MRI, lingering concerns about potential safety issues as well as hardware burdens ([27]). The steady translation of CMR technique to higher field strengths has brought numerous worthwhile innovations, all of which are accompanied by the accompanying rigor in terms of scan time, reliability, and safety that are a requirement for a successful clinical tool. Recent advances in multi-channel RF coils, pulse sequence design relying on parallel imaging strategy and robust imaging protocol, guidance to achieve good image quality in the settings of patient uniqueness, and image processing workflow have been alike crucial in establishing reliable clinical applications with routine scanning procedures and image interpretation all possible at high field. The scope of the imaging potential at ultra-high-field MR is further extended by free-breathing cardiac CINE imaging combined with prospective respiratory, real-time cardiac, and k-t acceleration.

Furthermore, with careful selection of dedicated prospective motion tracking and correction techniques, the overall efficiency of full 3D whole-heart coronary MRI has been enhanced, enabling high-throughput CINE imaging of coronary anatomy. Nevertheless, these approaches also place high demands on timing, parallel imaging interpolation, and, if necessary, increased receiver coil count. Upon adequately capturing the anatomy of the coronary vessel tree along with overall course and branching, as well as major variants in vessel anatomy, slice prescriptions for subsequent high-resolution steady-state free precession imaging can be derived, improving robustness against in-plane motion and flow-related signal dropouts.

7. Challenges and Limitations

Introduction of 7 Tesla MRI systems into clinical practice opens a new era in magnetic resonance where previously undiscovered contrast mechanisms can be exploited and novel techniques can be developed to further improve the capabilities of MRI examinations. Advanced development must be accompanied by continuous evaluation of the systems with respect to image quality and clinical interpretation. New challenges arise on all levels of system and methodology which need to be addressed. Investigating the mature technology of CMR^7T, the paper elaborates dominant hardware factors and system limitations affecting image quality and post-processing capabilities. Conducted early clinical studies and clinical conclusions suggest venues that need further investigation. In the past decade, the introduction of 7 Tesla MRI systems into clinical practice has opened a new frontier to magnetic resonance. The introduction of higher static magnetic fields enables today the implementation of a number of new technologies and approaches at 7 Tesla to explore previously undiscovered contrast mechanisms and to develop novel techniques to further improve the capabilities of MRI examinations. They are vivid in the recent rapid developments of more sophisticated pulse sequences, more versatile RF hardware, advanced human safety, accurate magnetic field modeling, flexible and efficient post-processing, and high-performance processing hardware. On all levels of MR systems and techniques, there are new challenges that need to be addressed for a successful development of the technology from the realm of research to clinical practice [26]. High-frequency RF-based pulse sequences can be translated into standard RF coils to fully utilize lower RF frequencies, thus, making contrast-enhanced techniques sensitive to different parameters such as T1, T2, or T2*, or even acquire visual stimuli using parallel acquisitions. The high potential of MRSI at UHF has already been shown in several clinical applications [17]. Schesle et al. proposed parameter mapping based on time-resolved MRF which not only optimizes the tradeoff between T2 and T2* mapping from an acquisition perspective but also advances quantitative mapping through improved reconstruction. New pruning strategy, regression model, and MRF oversight databases are being evaluated to improve the reconstruction speed of multi-parameter mapping from a post-processing perspective.

7.1. Technical Barriers to Implementation

UHF MRI is becoming a reality, despite significant technical challenges. The challenges of deploying UHF MRI systems and UHF-compatible RF coils have been met head on. System vendors, fabricator/technologist collaboration, clinical institutions, and educated patient populations are moving together to revolutionize neuroimaging. One of the most demanding areas in co-optimization between an ultra-high field MR scanner and RF coil is ultra-high field whole-body MRI. Whole-body UHF MRI, however, has the potential of early detection. The diseases of aging, such as atrophy, loss of white matter integrity, the silent buildup of iron deposits, incidence of prediabetes, and increased risk for a variety of conditions, start decades before symptoms appear [28]. It is hypothesized that by the careful design of UHF MRI procedures, potentially thousands of subjects could be screened yearly to identify cohorts needing preventive measures. MRSI using spiral readout acquisition in the human brain at 7 T presents a substantial advantage over lower field systems by offering a considerably improved opportunity to measure many metabolites within a reasonable scan time [17]. In spite of considerable advances in hardware and segmentation algorithms, the accurate and timely analysis of large numbers of high-dimensional and complex neuroimaging data still poses challenges to researchers. A large database of multi-backend persistent learning pipelines built on well-known methods can be employed with formal backend compatibility to ease switching and verification in practice. By emphasizing better user experiences, such intelligently designed AI-enhanced interactive software tools can materially assist neuroimaging researchers and clinicians. Multi-modal brain imaging at ULTRA high field MR is associated with the advantage of joint structural and metabolic fingerprints of both neurodegeneration and brain tumors cases in a unique fashion. Nevertheless, inverted T1-weighted space possibly contributes to the pumping of unbalanced tissue structural and metabolic fingerprints and emphasizes potential differences in advanced stage disease over pre-manifest or early stage pathologies without label.

7.2. Patient Safety and Comfort Considerations

Key concept in MRI scanner design is patient safety and comfort considerations. Safety aspects during MRI acquisition relevant to high magnetic field strengths such as SAR issues and RF coils are summarized. Patient comfort issues pertinent to human brain imaging systems are also discussed. For many patients, MRI may be the first and only experience with this imaging modality, and efforts have to be taken to ensure the comfort of the patients during their procedures. This is challenging because often an immersion approach has to be taken, such as a closed bore design, since that enhances the SNR and therefore reduces the scanning time. Nevertheless, as MRI becomes more widely available, a growing number of pediatric patients and patients with health problems will undergo imaging while awake, and system design has to take all of these issues into account [29]. Motion artifacts degrade MRI results. Motion of the patient leads to inaccurate characterization of the imaged anatomy or physiology, resulting in diminished image quality and diagnostic credibility. In structural MRI, motion affects image segmentation leading to an inaccurate brain label, and thereby to inaccurate estimates of regional gray matter volume and thickness. Therefore, large amounts of organizing a re-scan have to be taken [30]. Hence, it is of utmost importance to mitigate motion artifacts and to generate motion-robust image contrasts. A promising and widely applicable prospective motion correction technique consists of controlling the positions and orientations of the coils from which the k-space measurements are acquired in an automated manner. This technique is based on the assumption that a compact coil localization network can be trained offline with a limited amount of annotated calibration data. Once the system is deployed, coil localization is performed online using the same data but without annotation. This way prospective motion correction is possible with no tracking devices needed and additional calibration data is free of charge.

7.3. Cost and Accessibility Issues

Unconventional magnet technologies which can enable lower cost machine manufacturing, procurement, operations and reduced siting constraints/limits are essential for global MRI accessibility. Such unshielded, Passively Shielded or Joint-Feed magnet can be made very low cost. Low shelf cost options for making magnets affordable may utilize innovative methods such as permanent magnets hard-magnet or hybrid static magnet resistive+permanent magnets. Magnet designs which take advantage of deeper, lower, back-edge magnetic field areas could be much less expensive to produce than current systems. There are a number of techniques for producing open systems which can allow access to claustrophobic patients, children and with severe obesity. There are solutions which partly sacrifice performance for space, positioning flexibility or cost. Mechanical apparatus have also been developed for automated positioning over a high cost horizontal bed port using more conventional systems. Closed bore magnets of raster-scan-type which can accept a moving receiver or a bed, Van de Graaff type systems producing broad strokes or rapid pulsing of magnetic field sources, dual frequency systems which allow continuous tracking, systems with non-linear fields or time-pulse differentials which can move the magnetic-field detection beyond placed Picture Elements are just some examples. However, these systems are generally large, high cost and very powerful. This makes them inflexible and negates patient accessibility or mobility, particularly in Africa where being at or near the point-of-examination is crucial.

There are a number of groups developing hybrid medical platforms. Permuted contrast agents are also available which can leverage existing industrial imaging instruments. As these technologies develop at lower costs, the probability of African access becomes more realistic. Low-cost and smaller footprint MRI scanners may be developed for undergraduate education. Novel ideas may help in advancing high quality devices at significantly reduced equipment cost. The group has developed a low-power, 2D imaging platform with over thirty commercial deployment examples. There is a possibility that such machines may be considered as complement or adjuncts to existing medical imaging systems. The developing world is not as stochastic or low-rent as long classically pursed. They may be sources of low-cost ideas.

8. Future Directions in MRI Research

Ultrahigh field magnetic resonance (MR) presents opportunities and challenges for clinical practice. New hardware and software (workflow enhancement and reconstruction) applied to traditional contrast mechanisms can significantly improve the quality and efficiency of clinical imaging. Novel contrast mechanisms such as chemical exchange saturation transfer (CEST) MRI and sodium MRI are new directions for clinical and translational research [2]. Here, the main trends in the evolution of clinical MRI, such as the trends that allow increasingly high field strengths in clinical environments and the rapid expansion of imaging protocols by maximizing the potential of existing hardware/software, will be reviewed. Although there are still limitations that must be overcome for clinical or rapid real-time applications, at extremely high resolution the biological ultimate limits will be approached.

Novel software solutions can enhance the current practice of MR imaging. Fast parallel imaging reconstructions in combination with advanced coil designs and coil-array functionalities can significantly increase acquisition efficiency and improve motion correction applications. New scalable reconstruction frameworks can incorporate the paradigms of analytically optimized, domain-transform, and deep learning in a single reconstruction engine, demonstrating that effective artifacts reduction and ultrafast reconstruction could be achieved. More generally speaking, reconstruction methods that solve the inverse problem can be categorized as parametric (model-based) or non-parametric (learning-based). The former ones include analytical methods, iterative methods, and deep learning (i.e., supervised and unsupervised learning-based methods). The latter ones include untrained deep learning and implicit deep learning. Accelerated imaging can be achieved either via faster hardware or software solutions or a combination of both.

Hardware developments mainly focus on higher performance and larger coverage. More effective and more rigid RF coil designs have been developed than in prior studies. With the innovations in coils, multi-reference reconstruction calibration and noise-compensated reconstruction can significantly improve the imaging quality. Settlement of multifaceted 6G technologies can greatly enhance wireless data transmission. Thus, affordable and compact MR imaging systems are expected to be widespread in areas such as healthcare, life sciences, biology, and industry. There will be more and more mass-market MR technologies or products available.

8.1. Emerging Technologies in MRI

Emerging technologies in MRI rely on exploitation of the high spatial resolution, relatively fast acquisition, and high magnet-field images to create models with a limited number of parameters. In recent years, MRI scientists have developed many novel imaging technologies for zero- to lower-Fourier imaging faster and smarter using deep convolution neural networks. Continues demand for compact field-free-of-view MRI lead scientists to innovate a very low cost, single-snapshot, FOV MRI receiver using gradient coils, custom build low-cost receiver, pulse sequence, and image reconstruction algorithms. Involve in the development of new MRI acquisition techniques will help better understanding of various tissue microenvironments, discover the presence of cancer in it early stages, and eventually better tackle it preventing all the side effects of chemotherapy up to improbability of recurrences. Significant advancement of ultra-high field MRI technology will help neuroscientists and radiologists understand and characterize the development, maturation, and plasticity of the human brain, the visible gate of the mind. A technical description of a new RF coil design for visualizing small anatomical structures in rat brain for imaging options will be elaborated on. A new method based on Conventional Gradient-Based Spiral Acquisition with Parallel Phase Encoding Integrating Multi-Status Receiving Chains method for spherical brain visualization, again in subtractive and high sensitivity options, will be presented. A low-cost DAQ and RF generator development built around the platform maintains reliability while minimizing power consumption. These advancements will be detailed. Technical advancements in the photonic communication of a large elevated broadband near field sensor. Recent technological advancements in adhesive-free micro coupling. Application and utilization of digital micro mirror devices for advanced decoherence and readout techniques and development of noiseless integrated microwave amplification systems will be elaborated. Current technologies in building up physical qubit controls and designs for future fabrication will be introduced.

8.2. Integration with Other Imaging Modalities

Ultra-high-field (UHF) magnetic resonance imaging (MRI) offers great advantage for brain imaging with increased spatial and temporal resolution, improved tissue contrast and contrast-agent detection, and higher preclinical breast cancer models detection ability. A nitrogen-vacancy (NV) diamond magnetic field sensor with 300 nm spatial resolution and 1 nanoTesla sensitivity for 10 s detection time has been devised, which is capable of measuring Biologic Systems' magnetic resonance signals even with ultra-high-field NMR spectrometer or MRI magnet. Nitrogen-vacancy (NV) center in diamond is employed as a nanomagnetic field sensor for healthcare applications in in-vivo monitoring for biological systems like breast cancer models and Alzheimer's disease. Multiple imaging to study the interactions of different kinds of components provides a powerful approach. However, because of the lack of specific contrasts and registration problems between the imaging modalities, information fusion in spatial or frequency domains is difficult. Panelized encoding and contextual selective resonating in temporal and spatial domains are proposed to integrate enhanced MRI modality with nanoparticle-based multiphoton activation contrast agents and high-throughput scanning bio-distribution monitoring. Thus a clear view of the structure and metabolism of the cellular component at different spatial and temporal scales is provided. Integration with other imaging modalities is required as well for ultra-high field MRI with a parallel imaging brain's macromolecular proton imaging case [31] at 7 T clinical scanner.

8.3. Potential for Artificial Intelligence in MRI

Artificial Intelligence (AI) is a broad topic encompassing many different approaches, but, in general, using machine learning (ML) techniques can make it possible to extract complex patterns from a dataset. With machine learning, automated methods can be developed to extract quantitative information from cardiac magnetic resonance (CMR) images, while reducing the time required to analyze the acquired studies. Currently, the most prominent kernel-based models are based on Support Vector Machine algorithms, which have been successfully applied to identify diseases such as myocardial infarction and amyloidosis. However, these techniques can only categorize one data acquisition. The recognition of disease patterns from a set of multiple imaging values remains a challenge that can only be overcome by fully using AI models such as Convolutional Neural Networks (CNN) [32].

CNN-based models consider the images as a whole instead of evaluating each voxel separately. Therefore, they can significantly outperform traditional CNN-based approaches in the classification of diseases, as they have shown in otherwise familiar fields such as dermatology. Recently, CNN-based models have gained popularity in CMR and have been broadly used to automatically segment left ventricular (LV) endocardial and epicardial contours and myocardial fibrosis and be validated in multi-center cohorts. CNNs have successfully been applied to automate LV functional assessment, a key prognostic factor for cardiovascular morbidity and mortality. These systems act as a first-pass automatic analysis that is combined with expert review.

9. Ethical Considerations in MRI Research

The ethics of research using ultra-high field MRI are highly consequential given the new information they will uncover about the brain and genetic predispositions to diseases that will be difficult to screen for, predict, or attempt to modify using existing therapies. Therefore, the ethical issues require the highest level of attention, rigor, and inclusion of diverse perspectives [33]. Some examples of relevant questions include: Who should have access to such data? What repositories should be built to store data and other intellectual property? How should recruitment be conducted to ensure that marginalized communities get equal access to research protocols culture? What regulations should be put in place to guard against neuro-terrorism or changes in the brain that give one person an advantage over another? These questions cannot be completely resolved a priori. Most revolutionary innovations, whether in science and medicine, have outstripped ethical considerations and protections. Heightened awareness of ethical issues among research scientists, cognizance of a rapidly changing landscape, and emphasis on transparency and real-time discussion updates will be necessary. Inclusivity will be particularly important because those most in need of the proposed tests will undoubtedly be marginalized communities such as under-resourced, low income, or racially diverse groups. They must have equal access to the tests and their benefits. At the same time, every effort must be made to ensure that these groups are not exploited or allowed to volunteer for research protocols that pose greater overall risk than benefit to the community.

Consideration of explicitly de-identifying data for storage in public repositories will be critical. In addition, guarding against neuro-terrorism will require careful attention to how information will be disseminated, who will be able to access it, and what limitations will be placed on this access. Addressing how the data can be used commercially is also important. Adhering to guidelines for participants' storing and access to their information and intellectual property, as well as comparable guidelines in other companies, is essential as is creation of public liaisons to oversee all proposals for profit made to participants in these tests. Also, the potential impact of the implementation of rules for intellectual property currently only in simple academic settings should be envisaged.

9.1. Patient Consent and Data Privacy

Ethics guidance focuses on scientific openness and transparency while protecting human subjects. Ethical issues to consider as neuroimaging research using newly emerging portable ultra-high field MRI technologies are discussed. Guidance is provided on important ethical, legal, institutional, policy, and social considerations for researchers and others involved in such research. Neuroimaging technologies utilizing low- and high-field MRI systems are becoming smaller, cheaper, lighter, and more portable [33]. As they are developed and applied to research in diverse settings and populations, however, ethical, legal, and policy issues are increasingly being raised. Topics include patient consent and data privacy, intellectual property and benefit sharing, conflict of interest management, and broader risks to research and society.

While ethical issues are central to the responsible use of portable ultra-high field MRI technologies for neuroimaging studies, they can be difficult to predict and address proactively. Nevertheless, researchers should consider and address anticipated concerns to the extent possible. Researchers should ensure compliance with ethical, legal, institutional, and related policies prior to commencing studies utilizing portable ultra-high field MRI technologies. The aim is to help inform further deliberation and guidance on these and related technologies. Those involved in research using portable ultra-high field MRI technologies should consult resources on these considerations, be familiar with and adhere to applicable guidelines, and address new issues as they arise.

9.2. Equity in Access to Advanced Imaging

The widespread impact of unprecedented economic, racial, and geographic disparities in healthcare outcomes brought renewed attention to equity and justice issues. Advancements in neuroimaging, particularly MRI technology, have revealed new opportunities for understanding brain function and pathology, but access to these advances is not equitable. Current worldwide distribution of clinical MRI scanners points to an alarming underuse in low- and middle-income regions [34]. Addressing this imbalance from a technological angle requires both shortening the path to clinical capabilities and disrupting existing ones. New imaging technologies must serve health inequity, including a trained workforce and operative infrastructure for implementation in resource-constrained zones. High field magnets occupy a central place in MRI advancement, but the recent maturation of high-frequency, low-cost superconducting magnets banks confirm that every clinical scanner will not necessarily become a 7T+ magnet. Most areas serviced by 3T scanners have few, if any, worries about moving to 7T. Poorly served populations need accessible, high-quality, not necessarily state-of-the-art, may also lead to addressing a greater “brain” in environmental health and social equity questions. This requires consideration of both direction, type, and location of new Affordable, high-quality safety and health input provided by well-trained professionals is especially exigent in poorer regions. It is precisely at this intersection, between potential patient populations yet to be served by MRI content, and technology still yet to be commercially available, that a communications and business strategy has greatest chance of being mutually amazing and mutually useful [35].

10. Conclusion

MRI technologies at ultrahigh fields present unique opportunities for advancing our view and understanding of living tissues. A comprehensive overview of two recent contributions to technology and associated spectra at UHF MRI was presented. An example of how new MRI capabilities will increase the potential impact of this imaging modality in preclinical and clinical settings was given. These continued improvements will bring further advances in new scenarios for dedicated imaging instrumentation for preclinical UHF MRI. Innovative RF systems for direct regulation of spin precession and gyromagnetic ratio, and pulse sequences based on such principles have been demonstrated. Magnetization transfer contrast maps calculated from these novel pulse sequences have uncovered diverse stages of disease development in a model of Alzheimer's Disease. High-field isotropic diffusion contrast maps have demonstrated more pronounced differences in pathology among neurodegenerative diseases than existing approaches based on q-space or multi-shell diffusion protocols. When paired with distribution-function modeling to leverage the diverse measurement qualities available at UHF fields, such an advance may one day yield a more quantitative tissue-specific understanding of white-matter degeneration and the impact of stroke on subsequent plasticity and anatomy. In vivo diffusion tractography tied to specific fiber populations in the mouse brain has shown the ability to witness anatomical connections between brain regions, variations in connectivity as a result of pathology, white-matter changes throughout development, and even presence and severity of traumatic axonal injury. This revolution in understanding in vivo assimilation of memory and the genesis of neurodegenerative disorders would not have been possible at higher magnetic fields. Indeed, no one has witnessed these phenomena at less than 11.1T and many teaching, diagnostic, and research spectrometers remain well below that threshold. At 7T, translation to systems such as fMRI, PET-MRI, US-MRI, and other integrated modalities is already occurring. Widespread availability of contrast has yet brought 9.4T instruments into the core arsenal of many teaching hospitals (currently focusing on various musculoskeletal applications) would quickly lead to substantial and otherwise unattainable advances in overall understanding of normal function and microscale observations of diverse diseases across cardiac, vasculature, prostate, breast, CNS, bone and joints, Alzheimer's and other pathologies, and metabolism like cancer, diabetes, etc. These are truly exciting times for magnetic resonance.

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