Ultra-High Field Cardiovascular MRI: Future Directions

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The field of cardiovascular MRI (CMR) has evolved rapidly over the past decade, feeding new applications across a broad spectrum of clinical and research areas. The clinical need for speed and efficiency dictated by physiological motion and flow constraints has been a significant motivating force for the development of ever more rapid cardiovascular MR imaging techniques and advanced MR system hardware [1]. Today, a move towards widespread availability of high field MR systems (B_0=3.0 T) is underway [2-3]. Another development which is looming on the CMR research horizon is the move towards ultrahigh field, whole body MR systems ($B_0 \geq 7.0$ T) [4-13]. The gains in signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), imaging speed and efficiency associated with increases in field strength promise to not only to improve and streamline structural and functional imaging but also to facilitate targeted tissue characterization through molecular imaging and parametric mapping, and thereby to improve access to (patho)physiological processes and mechanisms.

Unfortunately, the image quality achievable at ultrahigh fields is not always exclusively defined by SNR considerations due to adverse effects of physical phenomena. For example, in current practice, some of the inherent advantages of ultrahigh field CMR are offset by the simple practical challenge of synchronization of data acquisition with the cardiac cycle using conventional ECG. Other practical impediments are associated with magnetic field inhomogeneities, off-resonance artifacts, dielectric effects and RF non-uniformities, localized tissue heating and RF power deposition constraints. All of these effects can undermine the benefits of ultrahigh field strengths, in many cases making it a challenge even to match the image quality of daily clinical routine CMR at 1.5 T. Still, the promise of increased spatial-temporal resolution afforded by ultrahigh field strength is a powerful motivator, since speed and signal may both be invested to overcome the fundamental constraints which continue to hamper some of the low field CMR applications. If practical challenges can be overcome, ultrahigh-field CMR will open the door to new approaches for both basic science and clinical research.

To this end, examples of ultrahigh-field CMR and their value for basic science and clinical research are provided in this presentation. Unsolved problems and unmet needs are also considered carefully, in an attempt to stimulate the community to throw further weight behind the solutions of remaining issues. Key concepts, technical

solutions and practical considerations for UHF CMR are outlined. Current trends, such as the trend towards multiple transmit architecture, the push towards local, many element cardiac optimized transceiver coil arrays (**Figure 1**), the use of rapid B_1-mapping/shimming techniques, and their implications for CMR applications are surveyed. Driven by the limitations and motivated by the challenges of conventional ECG, the need for novel cardiac gating/triggering technology [6, 12, 14-15] is discussed because early explorations into UHF CMR consistently reported R-wave mis-registration together with ECG triggering failure rates ranging between 20% and 80% [13, 16]. Realizing the constraints of conventional ECG, an alternative approach which uses the phonocardiogram for synchronization of imaging with the cardiac cycle [14-15, 17] is presented (**Figure 2**). Furthermore, demonstrable progress in UHF CMR technology and methodology is shown to provide further encouragement for the imaging community to tackle solutions of the many outstanding issues. Examples of early UHF CMR applications are introduced, including cardiac function assessment (**Figure 3**), coronary artery imaging and parametric tissue mapping with the ultimate goal to harmonize basic research carried out in the area of preclinical imaging with the needs of clinical imaging. A section of the presentation explores future directions fueled by an ever growing set of indications for CMR. here, economic and ergonomic requirements are likely to motivate shorter and less expensive magnets and novel radio-frequency hardware tailored for UHF CMR so that the current basic science efforts might eventually leave the engineering department and enter the clinical scenario. One important development on the hardware horizon is the advent of actively shielded 7.0 T MR systems, which will be far more compatible with installations in clinical imaging suites than current models used in basic research requiring hundreds of tons of shielding. Another intriguing development is the push to even higher fields used for CMR including 10.5 T and eventually 11.7 T. Of course, UHF MR is an area of vigorous ongoing research, and many potentially valuable developments will receive only brief mention here.

In summary, as 7T CMR applications become increasingly used for research, they should help to advance the capabilities of MRI for the assessment of heart disease. However it should be noted that CMR at 7.0 T is still in its infancy and needs to continue to be very carefully validated against CMR applications established at 1.5 T and 3.0 T. For example, first contrast agent passage perfusion imaging and late contrast enhancement studies have not been reported for 7.0 T yet. Although CMR at 7T is still an emerging area, it may be expected to continue to drive future technological developments. Taking the speed of progress into account an optimistic practitioner might envision a clinical role for tailored 7T CMR applications in the future, though this is, for the moment, merely a vision. It is nonetheless a vision that continues to inspire basic and clinical research into CMR at 7T. The field may still be evolving, but it is also maturing. The requirements of CMR at 7.0T are also likely to pave the way

for further advances in RF coil technology, including a broad move to multi-transmit MR systems equipped with 8 or more transmit channels. In short, while today's ultrahigh-field CMR techniques remain in a state of creative flux, productive engagement in this area continues to drive further developments.

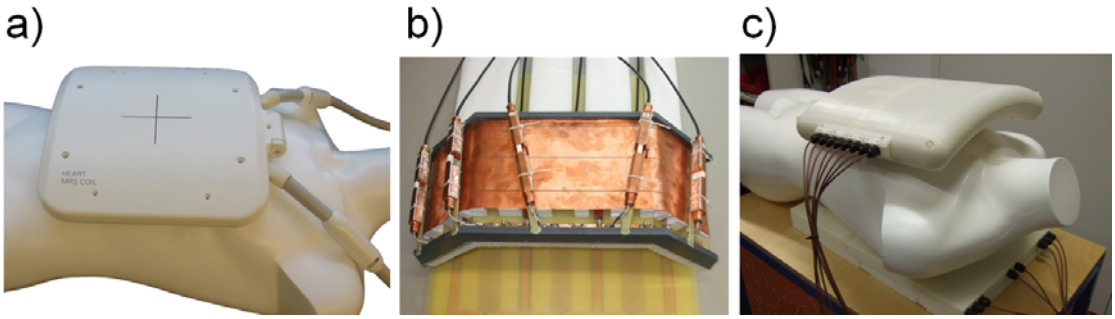

Fig. 1: Experimental versions and prototypes of cardiac optimized 7.0 T transceiver coil configurations that use loop elements including **a)** a 4 element TX/RX array, **b)** an 8 channel TX/RX coil design, which comprises five angled anterior plus three planar posterior loops and **c)** a two dimensional 16 channel transceive array.

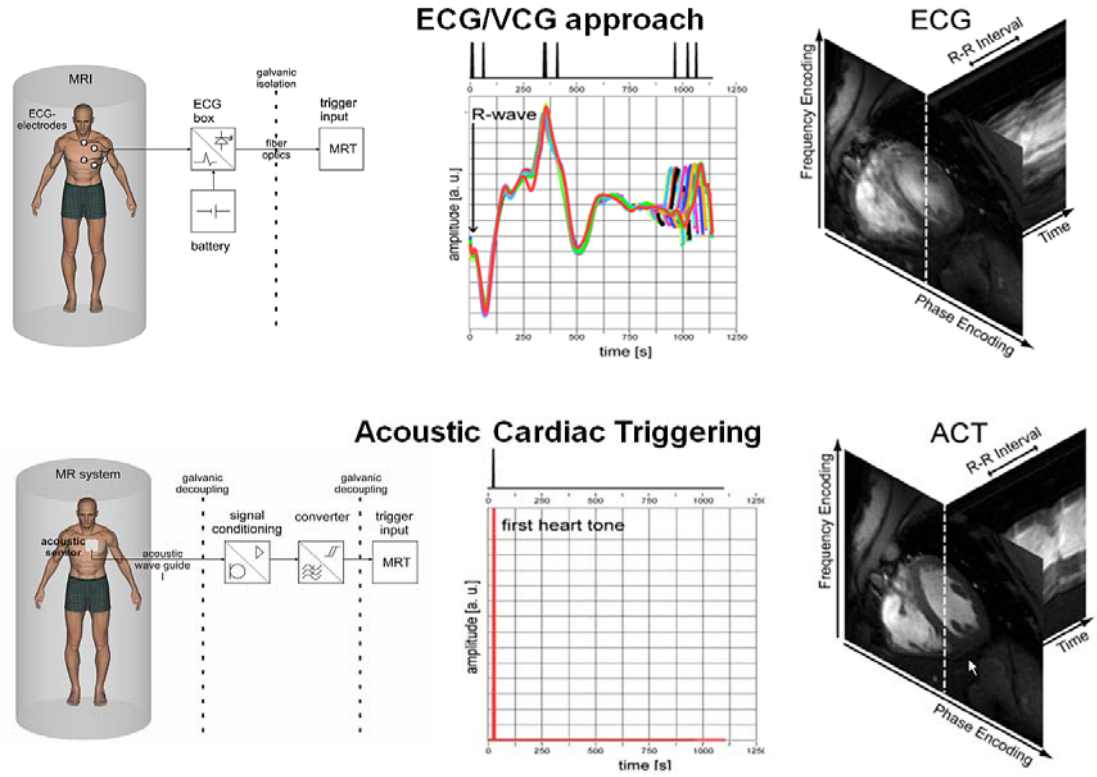

Fig. 2: Block diagram **(left)**, signal waveforms **(middle)** for **top)** conventional ECG gating and **bottom)** acoustic cardiac triggering (ACT). Interference by electromagnetic fields and magneto-hydrodynamic effects cause severe distortion in the vector ECG waveform, resulting in erroneous trigger recognition, which manifests itself in a severe jitter in the R-wave recognition. For comparison, ACT is free of

interferences from electromagnetic fields and magneto-hydrodynamic effects, and provides a reliable trigger signal free of jitter even in the presence of free breathing. Short axis views (right) derived from ECG (top) and ACT (bottom) triggered 2D CINE FLASH acquisitions at 7.0 T. Vector ECG triggered 2D CINE FLASH imaging was prone to severe cardiac motion artifacts if R-wave mis-registration occurred. Acoustic gating provided high-quality images free of cardiac motion effects.

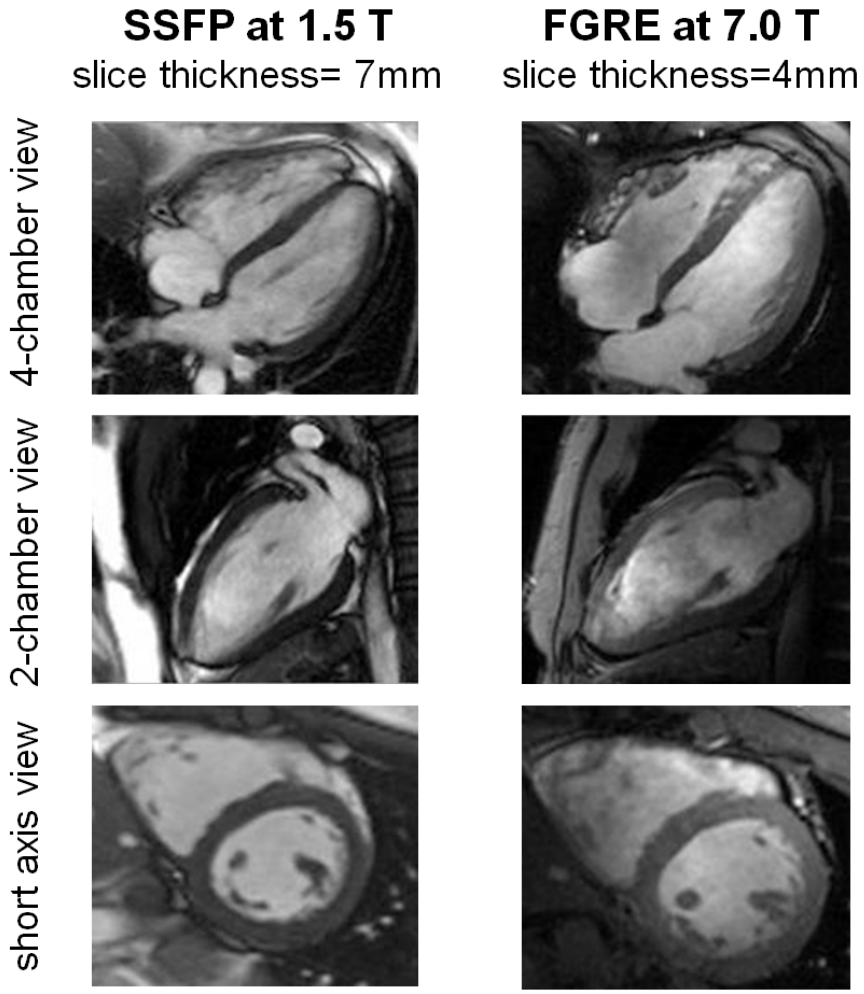

Fig. 3: Four-chamber view, two-chamber view and one midventricular short axis view derived from **left)** 2D CINE SSFP acquisitions at 1.5T using a slice thickness of 7mm and from **right)** 2D CINE FGRE acquisitions at 7T using a 4mm slice thickness.

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