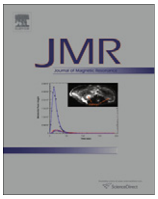
Journal of Magnetic Resonance 229 (2013) 208–222

Contents lists available at SciVerse ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr



# Progress and promises of human cardiac magnetic resonance at ultrahigh fields: A physics perspective

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ARTICLE INFO

*Article history:*
Received 3 October 2012
Revised 16 November 2012
Available online 29 November 2012

*Keywords:*
Ultrahigh field
Magnetic resonance
MRI
Multiple transmit
MR technology
Heteronuclear MR
RF coils
RF technology
7.0 T
Cardiovascular imaging
Cardiac MRI

ABSTRACT

A growing number of reports eloquently speak about explorations into cardiac magnetic resonance (CMR) at ultrahigh magnetic fields ($B_0 \geqslant 7.0$ T). Realizing the progress, promises and challenges of ultrahigh field (UHF) CMR this *perspective* outlines current trends in enabling MR technology tailored for cardiac MR in the short wavelength regime. For this purpose many channel radiofrequency (RF) technology concepts are outlined. Basic principles of mapping and shimming of transmission fields including RF power deposition considerations are presented. Explorations motivated by the safe operation of UHF-CMR even in the presence of conductive implants are described together with the physics, numerical simulations and experiments, all of which detailing antenna effects and RF heating induced by intracoronary stents at 7.0 T. Early applications of CMR at 7.0 T and their clinical implications for explorations into cardiovascular diseases are explored including assessment of cardiac function, myocardial tissue characterization, MR angiography of large and small vessels as well as heteronuclear MR of the heart and the skin. A concluding section ventures a glance beyond the horizon and explores future directions. The goal here is not to be comprehensive but to inspire the biomedical and diagnostic imaging communities to throw further weight behind the solution of the many remaining unsolved problems and technical obstacles of UHF-CMR with the goal to transfer MR physics driven methodological advancements into extra clinical value.

## 1. Introduction

A growing number of reports eloquently refer to explorations into ultrahigh field magnetic resonance (UHF-MR, $f \geqslant 298$ MHz) [1–10]. The novel technology tailored for UHF-MR, together with the eye-opening quality of the anatomical, functional and metabolic images of the brain, creates excitement among the imaging community and is the driving force for broader clinical studies. Already, recognition of the benefits and performance of UHF-MR technology has earned UHF-MR the moniker of being a steam engine for innovation. The clinical implications feed into a broad spectrum of neurology, neuroscience, neuroradiology, orthopaedics, radiology nephrology and other fields of clinical research.

To this end it is not as much of a surprise – as it appears to be at first glance – that UHF-MR can be beneficial for cardiovascular imaging as well [11]. Admittedly, the reports put forward are so far largely anecdotal. It is a fractal pattern, though, and a consistent story is starting to emerge. These developments are fueled by the signal-to-noise ratio (SNR) advantage inherent to higher magnetic field strengths and are driven by explorations into novel MR technology. Arguably, the potential of ultrahigh-field cardiac MR (CMR) is as yet untapped [11], and the advantages are sometimes offset by a number of concomitant physics related phenomena and practical obstacles associated with magnetic field inhomogeneities, off-resonance artifacts, dielectric effects and RF non-uniformities, localized tissue heating and RF power deposition constraints. It is no secret that these effects can make it a challenge to even compete with the capabilities of CMR at 1.5 T [11]. If these practical impediments can be overcome, the promise of enhanced relative spatial resolution – voxel per anatomy – afforded by UHF-CMR will open new avenues for MR based myocardial tissue characterization and imaging of the myocardial microstructure. The traits of UHF-MR will also help to go beyond conventional $^{1}$H imaging of the heart. These efforts include explorations into MRI/MRS of $^{23}$Na, $^{19}$F, $^{31}$P, $^{13}$C and other X nuclei to gain a better insight into inflammatory, metabolic and (nano)molecular processes of the heart.

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http://dx.doi.org/10.1016/j.jmr.2012.11.015

Realizing the progress and challenges of UHF-CMR in equal measure this *perspective* is not a literature review but an attempt to inspire the biomedical and diagnostic imaging communities to throw further weight on the unraveling of the many remaining unresolved problems and technical obstacles behind UHF-CMR. To meet this goal, this *perspective* outlines physical principles and current trends in MR technology tailored for UHF CMR. For this purpose multiple channel radiofrequency (RF) concepts are surveyed together with RF power deposition considerations. Practical concerns evoked by the paucity of data about RF heating induced by stents and implants at ultrahigh fields are considered. Early and frontier applications of CMR at 7.0 T and their clinical implications are explored.

## 2. Enabling RF technology for CMR in the short wavelength regime

### *2.1. Multi-channel transceiver radio frequency coils*

Constraints dictated by the physics of the applied radio frequency (RF) fields at higher frequencies constitute a challenge for UHF-CMR. The shortened wavelength ($\lambda$) of the RF fields in tissue reaches the dimensions of the target region, giving rise to destructive and constructive interferences, in other words focusing and distortion of RF fields, with a wavelength of

$$\lambda_{\text{myocardium}} = \lambda_{\text{vacuum}}/(\mu_r \varepsilon_r)^{1/2} \approx 13\ \text{cm} \tag{1}$$

at 7.0 T assuming $\mu_r = 1$ for the relative permeability and $\varepsilon_r = 60$ for the relative permittivity of myocardial tissue. In comparison, $\lambda_{\text{myocardium}}$ is approximately 54 cm at 1.5 T, which matches the size of the upper torso and which largely exceeds the size of the heart. As a deep-lying organ surrounded by the lung and other inhomogeneous tissue structures within the comparatively large volume of the thorax, the heart is particularly susceptible to conductive and dielectric effects in tissue at 7.0 T. In this regard Fig. 1 benchmarks the $B_1^+$ field generated by a 7.0 T cardiac coil versus its kindred 1.5 T and 3.0 T counterparts and highlights the electro-dynamic phenomena caused by wavelength shortening at 7.0 T. RF field focusing and distortion [12] that accompany UHF-MR typically manifest itself in non-uniformities of the RF transmit component ($B_1^+$). Non-uniformities in $B_1^+$ can cause shading, massive signal drop-off or even signal void, all of which bear the potential to spoil the benefits of UHF-CMR due to non-diagnostic image quality. The RF inhomogeneities in the thorax are generally so significant, in fact, that traditional birdcage body coils are no longer used for signal excitation at 7.0 T, and large volume body coils are not even provided with 7.0 T scanners.

The use of multi-channel transmission [13–16] is prudent to tackle the electro-dynamic effects at UHF-CMR with the ultimate goal to attain clinically acceptable image quality. This need has inspired explorations into novel radiofrequency (RF) technology including cardiac optimized multi-channel transmit/receive (TX/RX) configurations [17–21]. Multi-channel transmit/receive arrays run the trait of independent transmit coil elements that support exquisite control over the electromagnetic fields by modulating amplitude and phase used for excitation of each transmit channel independently. The basic concept of using a plurality of RF coil elements for selective control of relative phase and/or amplitude has been devised in 1984 [22]. It has been furthered to the concept of an amplitude and phase control network using MOSFET RF power amplifiers on each rung of a transverse electromagnetic (TEM) type coil being driven by its own power amplifier via a sliding contact [23]. Early applications of multi-transmit include the generation of excitation fields suitable for RF hyperthermia [24].

Serious efforts have been devoted to the development of multi-transmit surface RF coil arrays tailored for UHF-CMR. These developments make use of a variety of building blocks that include strip line elements, loop elements or radiative elements. Recent reports stated, that radiative antenna exhibit pronounced RF power deposition constraints versus loop elements since the loop coil can distribute its deposited energy over a larger surface [25]. In comparison, microstrip antennas have been reported to show RF power deposition levels that exceed that of a dipole antenna by factor 4–7 when normalized to $B_1^+$ [25]. These results are a valuable contribution to the ongoing debate on the ultimate RF coil element design; a debate that is intended to spur novel RF coil concepts.

Transceive strip line arrays tailored for UHF-CMR have typically been laid out on rigid or semi-flexible frames. In one pioneering design, each element in an 8 element TEM transceiver array was connected to a dedicated RF power amplifier [17]. Other configurations of cardiac optimized 7.0 T transceiver arrays run flexible designs consisting of a pair of four-element or eight strip line arrays, one placed anterior and the other posterior to the torso [18,26], with element spacing carefully selected for decoupling.

Other cardiac-optimized 7.0 T transmit-receive configurations use loop elements with the number of independent elements increasing from 4 to 32. A recently proposed 4-channel TX/RX design exhibits two anterior and two posterior elements as illustrated in Fig. 2 [19]. Another report describes an 8-channel TX/RX coil that comprises five anterior elements as shown in Fig. 2 [27]. For both configurations the elements are arranged in a one-dimensional array which limits the degree of freedom for perfecting $B_1^+$ uniformity. For this reason a 16-channel TX/RX coil was proposed which involves eight anterior and eight posterior elements each laid out on a 2 by 4 two-dimensional grid as illustrated

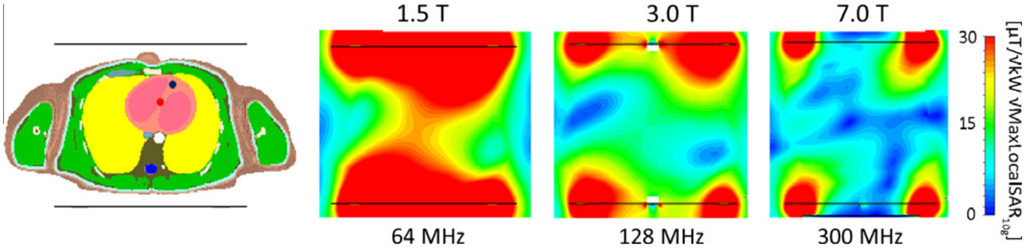

**Fig. 1.** Frequency dependence of $B_1^+$ distribution and RF power deposition. $B_1^+$ efficiency distribution scaled to the maximum local SAR of a cardiac optimized 4-channel coil array at 1.5 T, 3.0 T and 7.0 T. For each configuration identical phase settings are used for $B_1^+$ and local SAR (10 g average, 1 W input power) calculations. The $B_1^+/\sqrt{\text{kW}}/\sqrt{\text{max local SAR}_{10g}}$ distribution is shown for three discrete MR frequencies; 64 MHz (left), 128 MHz (middle) and 300 MHz (right) and normalized to an efficiency of 30 $\mu\text{T}/\sqrt{\text{kW}}\sqrt{\text{W/kg}}$. $B_1^+$ uniformity is substantially reduced for the short wave length regime at 7.0 T. For the maximum input power of the coils, which is dictated by MR safety regulations that forbid overriding of maximum local SAR, a lower $B_1^+$ field is generated when moving from 1.5 T to 7.0 T. This implies that a higher average power is required for the excitation pulse to reach the same flip angle at higher MR frequencies. Given a higher average power and assuming that TR is not prolonged, RF power deposition shows to be significantly enhanced at UHF-MR frequencies.