Progress of MRI-guided EP Interventions is Hampered by a Lack of ECG-based Patient Monitoring – An Engineering Perspective

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Abstract: This position paper discusses the current developments and advances of electrophysiological (EP) interventions guided by magnetic resonance imaging (MRI) and the associated technological challenges and difficulties which need to be overcome in the future. MRI provides several advantages compared to other medical imaging modalities. However, performing any kind of intervention or surgery in an MRI scanner is technical challenging. EP procedures are a special case since they involve many sensitive electronic stimulation and measurement devices and also require a high quality patient monitoring. Monitoring the patient's electrocardiogram (ECG) inside an MRI is a challenging task due to the MRI's hazardous environment. Hence, ECG signals are highly distorted and are of limited diagnostic value. This limitation in ECG-based patient monitoring and the lack of a fully functional, MRI-conditional 12-lead ECG hampers or delays the progress of EP procedures during MRI. We review and discuss the main reasons for this limitation and give an outlook and recommendation for further research approaches.

1 INTRODUCTION

Magnetic resonance imaging (MRI) is a medical imaging modality which is used for a wide range of diagnostics purposes such as the identification of cancer tumors, for cardiovascular diseases or the function of the brain. Cardiac MRI (CMR) is one very important application of MRI used to study the anatomical and functional properties of the heart muscle and the related blood vessels. In addition to its diagnostic usage, MRI has a high potential for guiding minimally interventions, where it is referred to as interventional MRI (iMRI) (Barkhausen et al., 2017). One type of these interventions are electrophysiological (EP) procedures which are used to diagnose and treat malfunctions of the cardiac's electrical generation and conduction system. EP procedures are minimally invasive interventions, which are until now guided by X-ray or flouroscopy. Specialized electrode catheters are used to measure the electrical potentials at the inner surface of the heart. Depending on the type of diagnosis, treatment can be performed subsequently, e. g. by ablation catheters. EP procedures could benefit from the advantages provided by MRI (Lederman, 2005).

For performing an EP procedure under MRI-guidance, patient monitoring is a crucial aspect. One of the most important physiological signals in an EP procedure is the patient's electrocardiogram (ECG) (Haines et al., 2014). However, acquiring, processing and analysing an ECG during MRI is a challenging task whereas the diagnostic value of the processed ECG is nowadays very limited (Oster and Clifford, 2017).

We represent the position that the lack of reliable, ECG-based patient monitoring is one of the reasons why the progress of MRI-guided EP interventions is hampered and slowed down. In order to discuss our position and perspective, this paper gives an overview of trends in MRI-guided EP interventions, reviews the currently existing challenges and gives a broad outlook on future developments in terms of hardware and software.

2 BACKGROUND

2.1 Patient Monitoring in MRI

Patient monitoring during MRI exams or interventions is a crucial task which is hampered by the hazardous MRI environment. Several vital signs

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of a patient can be monitored such as invasive and non-invasive blood pressure, respiration, gas analysis, oximetry, body temperature, or the ECG. There a several conditions under which the vital signs of a patient should be monitored, among them: sedated patients, critical care patients, patients which are unable to communicate, or patients undergoing an interventional MRI.

During the last two decades, the demand for high-quality patient monitoring systems raised due to the potential and new applications of MRI and MRI-guided interventions. This includes interventions such as catherizations or biopsies (Razavi et al., 2003; Ratnayaka and Lederman, 2010; Fischbach et al., 2013) and MRI-guided EP interventions (Dukkipati et al., 2008; Schmidt et al., 2009; Koopmann and Marrouche, 2013; Piorkowski et al., 2013; Chubb et al., 2017; Elbes et al., 2017; Mukherjee et al., 2018; Sommer and Mont, 2018).

The following sections briefly review MRI-guided EP procedures, give an overview of available or necessary equipment to perform interventions in this environment and elucidate the need for a reliable, diagnostic ECG during MRI.

2.2 MRI-guided EP Procedures

Opposed to X-ray imaging or fluoroscopy, MRI provides a superior soft tissue contrast, allows a 2D, 3D or 4D visualisation of the heart and other organs and is used as a standard diagnostic tool for a wide range of medical applications. Considering interventional EP procedures, MRI provides additional diagnostic information. It enables the detection of scar tissue which can be found in patients with ventricular tachycardia (Stevenson, 2009), or of febrosis seen in patients with atrial fibrillation (Mewton et al., 2011; Dzeshka et al., 2015). MRI also has the potential to visualise lesions induced by radiofrequency ablation (Vergara et al., 2011; Hunter et al., 2013).

The benefits of an MRI-guided EP can be summarized as follows: *1)* improved substrate identification resulting in a more precise ablation targeting, *2)* improved guidance during the intervention and *3)* an improved assessment of the lesion formation after an ablation (Chubb et al., 2017).

CMR enables the *identification and differentiation of atrial and ventricular arrhythmogenic substrate*s (Ashikaga et al., 2007). This information is increasingly used for guiding cardiac interventions. It would be even more helpful and expedient when it is directly available during the EP procedure.

Procedure guidance can be improved by CMR compared to the conventional, established approaches. Currently, the more complex EP procedures are performed by combining X-ray flouroscopy (for anatomical guidance) and electroanatomic mapping techniques. The structural information provided by this approach is inferior to the anatomical and functional information achievable by CMR. CMR provides more detailed information about the chamber of interest but also about surrounding structures such as coronary arteries.

Evaluation of ablation lesions is another potential advantage of CMR over the other imaging modalities. CMR could directly be used to assess acute ablation lesions instead of a post-procedure analysis.

2.3 Selected iMRI Equipment

Performing an MRI-guided intervention in general and a cardiac intervention in particular requires dedicated hard- and software. Starting with the basic requirement, i. e. the MRI scanner, a wide-bore MRI scanner with 1.5 T or 3 T is the most common choice nowadays. Open bore MRI scanners systems would be ideal for any kind of intervention but their production was unfortunately discontinued (such as Philips' Panorama HFO 1 T or GE's SIGNA SP 0.5 T Open Configuration). For displaying MR images inside the scanner cabin, in-room displays are either provided by the scanner manufacturers or by third party companies. The scanner vendors also provide software supporting the interventions, such as the Interactive Front End (Siemens, Germany) or the iSuite (Philips Research Hamburg, Germany). Basic hardware for patient monitoring is often included in the MRI scanner system, such as a simple ECG mainly used for triggering image sequences, a PPG or a respiratory belt system. Third party patient monitors include further parameters such as noninvasive and invasive blood pressure measurements, CO_2, temperature and anaesthesia gases. Exemplary MRI specific patient monitoring devices are the Tesla M3 (MIPM GmbH, Germany), the Maglife Serenity (Schiller AG, Switzerland) or the Expression MR400 (Philips, The Netherlands). Besides patient monitoring, MRI compatible anesthesia carts are available, e. g. the Aestiva/5 MRI (Datex-Ohmeda, GE Healtcare, USA). For performing MRI-guided EP procedures, one MRI-specific ablation and monitoring system is currently available including an ablation catheter and a recording/stimulation system (Imricor Medical Systems, USA). In general, the wide range of tools available for X-ray guided interventions such as different catheters, guidewires, tracking systems, ablation generators and others are not available for the MRI environment yet.

For enabling a complete cardiac monitoring, several companies and research institutions are working on 12-lead ECG systems and hemodynamic monitoring platforms since many years or even more than a decade. But none of these systems is commercially available or has an FDA clearance or approval. Examples are the PELEX-MAX (PinMed, USA), the MiRTLE system (MiRTLE Medical, USA) or ACDx system (All Clear Diagnostics, USA). There are also open source research systems such as the Physiological Recording in MRI Environment (PRiME) system (Kakareka et al., 2018). None of these systems can currently provide a diagnostic ECG. The reasons for this circumstance will be explained in the following sections.

3 ECG IN MRI - CHALLENGES

The different types of magnetic fields in an MRI scanner severely distort the acquired ECG signals. The signals picked up by the ECG electrodes in an MRI can be summarized as follows (Felblinger et al., 1999):

$$S(t) = S_{\mathrm{ECG}} + S_{\mathrm{MHD}} + S_{\mathrm{G}} + S_{\mathrm{IND}} \tag{1}$$

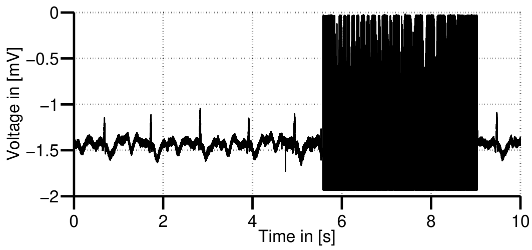
where S_{ECG} is the ECG signal, S_{MHD} is the signal caused by the magnetohydrodynamic (MHD) effect, S_{G} are gradient distortions and S_{IND} are other induced distortions or noise. Inductions (S_{IND}) can occur when the ECG recorder or the cables are moved due to respiratory motion. Other sources of induced distortions are the time-varying, switched gradient magnetic fields and the MRI scanner's RF fields. The RF fields of clinical scanners have a frequency of $f = 42.58\,\mathrm{MHz/T} \cdot \mathrm{B}_0$ where B_0 is the static magnetic field strength. This frequency is far beyond the ECG's frequency range (approximately 0.05 Hz-150 Hz). Distortions due to the RF fields can be caused by demixing effects in analogue electronic circuits. The influence of the RF fields can be reduced by a proper shielding of the ECG hardware (Oster et al., 2010b). This article only considers distortions induced by the switched gradient magnetic fields and the MHD effect.

3.1 Switched Gradient Magnetic Fields

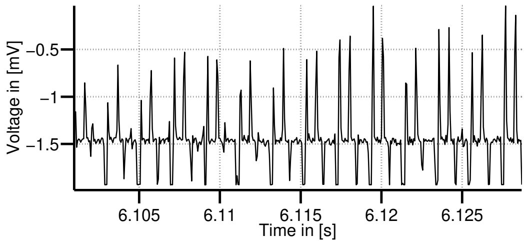
The distortions induced by the switched gradient magnetic fields are given as

$$S_{\mathrm{IND}} \approx S_{\mathrm{G}} \left(\frac{\partial G_x(t)}{\partial t}, \frac{\partial G_y(t)}{\partial t}, \frac{\partial G_z(t)}{\partial t} \right) \tag{2}$$

where $G_x(t), G_y(t), G_z(t)$ are the gradients used for image acquisition. The time-varying magnetic fields



(a) ECG trace with gradient artefacts.



(b) Zoomed view of (a) showing a closer view of the artefact properties.

Figure 1: Gradient artefacts during an MRI sequence (gradient echo).

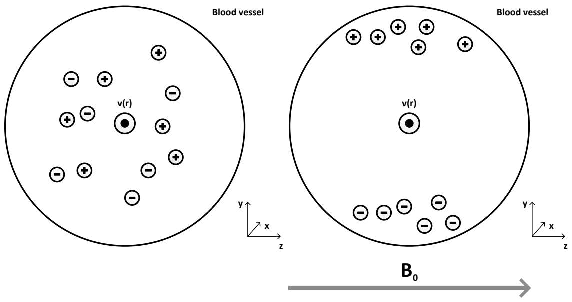
induce voltages directly within the human torso but also in the surface spanned by the ECG cables (Laudon et al., 1998; Felblinger et al., 1999). Figure 1 shows an exemplary ECG with a gradient induced distortion during an MRI sequence.

Applying an QRS detection algorithm to such an ECG signal without further preprocessing would result in a high number of false positive and false negative detections due to the high amount of distortions and the QRS complexes hidden within them. Hence, suppressing or removing the signal distortions originating from the time varying switched gradient magnetic fields is usually the first signal processing step.

3.2 The Magnetohydrodynamic Effect

The MHD effect results from the interaction between the pulsatile blood flow, which is caused by the rhythmic action of the heart and the static magnetic field of the MRI scanner, B_0. Blood plasma, which makes up about 60 % of the total blood volume, contains approximately 10 % solutes including electrolytes such as Na^+, Cl^- or HCO_3^- ions and non-electrolytes (glucose, urea). The ions (electrolytes) are moving inside the vessels where they experience a force due to the presence of the MRI scanner's static magnetic field. This force is known as Lorentz force, $\vec{F}$, where the force per charge is given as

$$\frac{\vec{F}}{q} = (\vec{v} \times \vec{B}). \tag{3}$$



(a) Outside the MRI (b) Inside the MRI

Figure 2: A simplified schematic of the MHD effect inside a blood vessel. Positive and negative ions are moving with the velocity $v(r)$ along the blood vessel where r is the vessel's radius. Outside the MRI scanner, ions are randomly distributed inside the vessel (a). Inside the MRI scanner (under the influence of the static magnetic field), the ions experience the Lorentz force (b).

It depends on the magnitude and orientation of the blood flow velocity $\vec{v}$ of the charged particles q with respect to the $\vec{B}_0$ field. This force causes the ions to move perpendicularly to the direction of the blood flow and perpendicularly to the MRI scanner's static magnetic field. The ions accumulate near the vessel's wall leading to a potential difference across the vessel that can be expressed as

$$V \propto \int_0^l \vec{v} \times \vec{B}_0 \, d\vec{l} \quad (4)$$

where l is the diameter of the vessel. The voltage estimated using Eq. 4 is called Hall voltage. Figure 2 schematically shows how the static magnetic field B_0 affects the moving ions inside the cross section of a blood vessel. The resulting body surface potentials of the MHD effect superimpose the ECG signal. Figure 3 summarizes several physiological and technical parameters which influence the MHD effect.

When the ECG is measured inside an MRI scanner, the MHD effect mainly affects the segment between two QRS complexes, i. e. the ST-segment, the T-wave and the P-wave. Exemplary ECG signals from two different subjects acquired outside and inside a 3 T MRI scanner are shown in Fig. 4. Since the MHD effect is directly related to the blood flow, it mostly affects the ECG during the ventricular systole where the blood is ejected from the ventricle into the aorta and pulmonary artery. Hence, the diagnostic information contained in the ECG's ST-segment and T-wave is hidden by the MHD effect which reduces the diagnostic value of the ECG during an MRI exam or intervention. For MRI scanners with magnetic field strengths ≥ 7 T, QRS detection can be hampered due to the large magnitude and slope of the MHD effect (Krug et al., 2013).

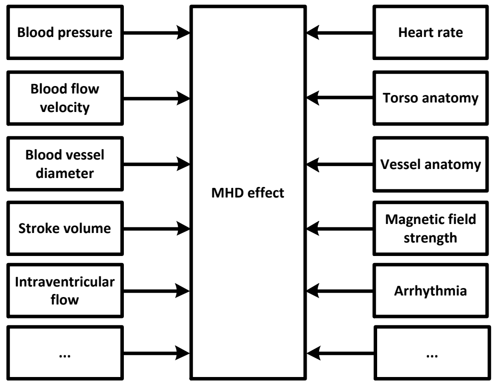
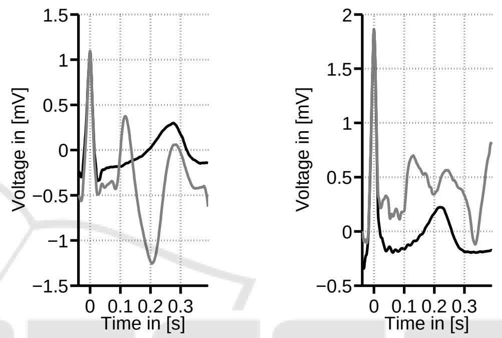


Figure 3: Selected physiological and technical parameters affecting the MHD effect.



(a) Subject A (b) Subject B

Figure 4: Comparison of the ECG signal waveform in lead II in two different subjects acquired outside (black) and inside (grey) a 3 T MRI scanner. The QRS complexes are aligned at $t = 0$ s. The MHD effect mainly affect the ECG's ST-segmentand T-wave.

4 CURRENT SITUATION

MRI specific ECG systems are available from different MRI scanner manufactuers and third party vendors. These systems enable the acquisition of ECG signals under different conditions, i. e. under the presence of different magnetic field strengths and various imaging sequences. It can be considered that safety issues, especially due to RF-induced cable heating, play a negligible role nowadays. The different vendors optimized the ECG electrode positions (close proximity to the heart), cable resistances (50 kΩ to 100 kΩ), shielding of the electronics and data transmission in order to obtain a robust signal acquisition system. A very extensive overview and summary of these aspects is given in (Oster and Clifford, 2017). The acquired ECG signals are contaminated by the effect described in Section 3. Figure 5 briefly summarizes different signal processing steps depending on the usage of the ECG in MRI.

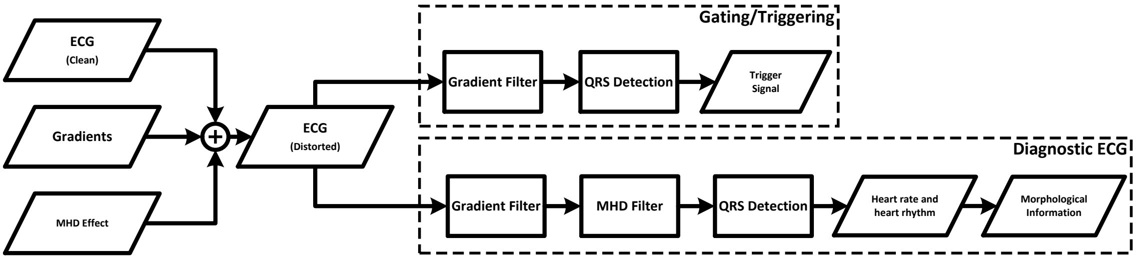


Figure 5: Signal acquisition and processing chain. For diagnostic purposes, the MHD effect has to be filtered after gradient filtering in order to enable a morphological analysis of the ECG.

Gradient filtering is usually the first processing step. Several dedicated filtering methods exist to achieve this goal, e. g. based on independent component analysis (Oster, 2009; Oster et al., 2009b), adaptive filtering (Kreger and Giordano, 1992; Laudon et al., 1998; Felblinger et al., 1999; Abächerli et al., 2005; Odille et al., 2007; Wu et al., 2011), Bayesian filters (Oster et al., 2010a; Oster et al., 2010b) or median filtering (Schmidt et al., 2018). The quality of the different filtering approaches is difficult to compare since it depends on the signal acquisition hardware, the electrode placement and the wire configuration, sampling rate, analogue filtering stages and others. Hence, patient monitoring device manufacturers employ different methods optimized for their specific systems and hardware.

QRS detection: Once the gradients are filtered from the ECG, the ECG is still superimposed by the MHD effect. Without further filtering of the MHD effect, QRS detection is possible in most cases. Dedicated QRS-detection algorithms were developed in the past to cope with the MHD effect enabling a reliable QRS detection with a minimized number of false positives. An early method was based on the vectorcardiogram (VCG) (Fischer et al., 1999), which allowed a spatial separation of the ECG and MHD signal components. Because of certain limitiations of the VCG based method at higher magnetic fields strengths ($\geq$7 T), a modfified VCG based approach was proposed (Krug, 2015). Wavelets were employed for QRS detection by means of frequency decomposition (Abi-Abdallah et al., 2006; Sabbah et al., 2007) or singularity detection (Oster, 2009; Oster et al., 2009a). Higher order statistics were used to detect the high slopes of the QRS complex and suppress the MHD effect (Schmidt et al., 2014).

MHD filtering: To reach the ultimate goal of having a fully diagnostic ECG during MRI, MHD filtering is the most crucial and most challenging aspect in the whole signal acquisition and processing chain. As described in Section 3.2, the MHD effect is mainly caused by the blood flow in the aorta and is highly correlated with the ECG signal and the cardiac cycle. The ECG signal – which has its origin in the depolarization and repolarization of the cardiac cells – and the MHD effect can be considered as spatially separated sources. The spatial segregation of both sources makes the problem ideal for source separations techniques such as independent component analysis. Although this method was successfully applied to simulated data (Bhatt and Reddy, 2009), it failed with real 12-lead ECG signals (Krug et al., 2012). The reason for that is that the different sources highly depend on each other. The problem of MHD filtering was also tackled by adaptive filters (Tse et al., 2014). However, this method requires a-priori knowledge about different patient specific heart beat morphologies used to train the adaptive filter. Such data is usually not available during a real measurement. The most recent research on MHD filtering employs a Baysian filtering approach in which the ECG and MHD signal contributions and their (pseudo)-periodic nature are modelled (Oster et al., 2013; Oster et al., 2015). The method was applied to simulated and real ECG datasets contaminated by the MHD effect where it was shown that it is able to detect simulated pathological alterations of the ECG such as the elongation of the QT-interval.

5 DISCUSSION AND OUTLOOK

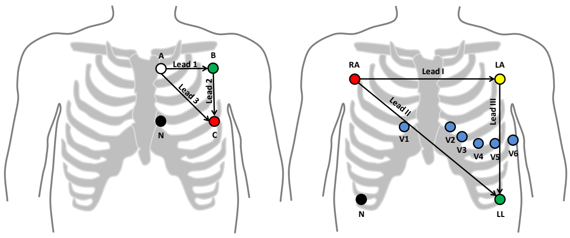
Considering all the potential advantages and benefits of an MRI-guided EP procedure compared to a fluoroscopy-driven intervention, one may ask why MRI nowadays is rarely used for these interventions. Several reasons can be given for the comparatively slow progress in this field: *1)* lack of MRI compatible EP hardware, e. g. electrode catheters, ablation catheters, ablation generators, external defibrillators, *2)* patient monitoring hardware and signal processing algorithms and *3)* trained staff to perform interventions in the MRI environment.

The aim of this paper was to emphasize that a diagnostic ECG is indispensable for the serious establishment of MRI-guided EP procedures. Tremendous advances were made in the last two decades including the development of acquisition hardware as well as the software for gradient artefact removal and QRS detection. Triggering image sequences and monitoring the patient's heart rate are still the most common applications of an ECG during MRI. Hence, only few research was invested in providing a comprehensive diagnostic (12-lead) ECG within the MRI scanner.

Currently, several prestigious heart centres around the globe have the ambition to establish or transfer certain EP procedures from X-ray fluoroscopy to MRI. For this transition, a diagnostic ECG is one of the key elements. To achieve this goal, the authors identified two important issues or aspects which need to be pursued or addressed by the international research community as well as by the monitoring vendors: *1)* the development of an MRI-compatible standardized 12-lead ECG and *2)* the suppression of the MHD effect.

Several cardiac interventions require a 12-lead ECG for an optimal disease diagnose or treatment. Providing a 12-lead ECG in the MRI bore will be challenging from the hardware development and signal processing point-of-view due to additional ECG leads, cables and electrodes, larger electrode distances (Einthoven triangle) and additional electronics. Current ECG systems used in the MRI scanner are designed to reduce the influence of the switched gradient magnetic fields and the MHD effect, basically by a minimization of the electrode distances. Figure 6 compares the electrode placements of different lead systems. Changing from an MRI-optimized lead system to a conventional 12-lead ECG system will imply several new problems due to increasing signal distortions. Hence, new signal processing algorithms or techniques will be required to cope with these new problems. Having a 12-lead ECG would facilitate the establishment of MRI-guided EP interventions. In a first step, when the MHD effect is still present, a 12-lead ECG would enable to perform EP-procedures mainly requiring information about the QRS-complex, e. g. the diagnosis and treatment of ventricular tachycardia. Other interventions requiring a more detailed morphological analysis of the ECG such as the P-wave or T-wave could not be performed at this stage.

The major challenge for the research works within the next years will be a reliable suppression of the MHD effect. Much research is necessary for investigating and developing new signal processing techniques to tackle this problem. Proper experiments and studies have to be designed in order to collect appropriate ECG data from various subjects under different



(a) Reduced lead set (b) 12-lead ECG

Figure 6: (a) Typical ECG lead system used during MRI exams and (b) the conventional 12-lead ECG system comprised of the Einthoven triangle and the precordial leads.

conditions. Most experiments conducted in the past are based on data from healthy subjects, i. e. in the absence of cardiac arrhythmias or pathologies. This is the most important limitation of the works performed in the recent years. One of the most crucial aspects with the design of the experiments is the fact that the measurement of an ECG with or without the MHD effect is not possible under the same condition, i. e. the ECG during a sudden, unexpected arrhythmic event will be either measured inside or outside the scanner. However, especially the unforeseen, unknown arrhythmic episodes where the ECG and MHD signal components change at the same time are the most interesting aspect to be studied in the future.

From the authors point of view, the ECG is one of many elements which play a key-role for the establishment of MRI-guided EP procedures. It is essential for successful accomplishment of these procedures and for a positive patient outcome. The development and establishment of an MRI-compatible 12-lead ECG will come along with several technological challenges but it will enable the establishment of certain EP procedures using MRI. Once certain procedures are established and their potential is more visible to scanner manufacturers and medical device providers, it can be assumed that this will lead to increasing development efforts in this field.

In addition to a reliable diagnostic ECG, other components such as catheter tracking, ablation and electrode catheters, ablation generators or external defibrillators need to be developed or adapted in order to be operated under the very special conditions of the MRI environment. MRI scanner manufacturers need to provide appropriate real-time sequences, the integration of tracking solutions and an adapted workflow to enable a smooth and efficient conduction of the EP procedures. Only with a combination of different hardware and software developments and close collaboration between scanner manufacturers and third-party companies, the amazing and promising field of MRI-guided EP procedures can be made accessible.

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