Brief Report

FLASHlight MRI in real time—a step towards Star Trek medicine

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Abstract: This work describes a dynamic magnetic resonance imaging (MRI) technique for local scanning of the human body with use of a handheld receive coil or coil array. Real-time MRI is based on highly undersampled radial gradient-echo sequences with joint reconstructions of serial images and coil sensitivity maps by regularized nonlinear inversion (NLINV). For this proof-of-concept study, a fixed slice position and field-of-view (FOV) were predefined from the operating console, while a local receive coil (array) is moved across the body—for the sake of simplicity by the subject itself. Experimental realizations with a conventional 3 T magnet comprise dynamic anatomic imaging of the head, thorax and abdomen of healthy volunteers. Typically, the image resolution was 0.75 to 1.5 mm with 3 to 6 mm section thickness and acquisition times of 33 to 100 ms per frame. However, spatiotemporal resolutions and contrasts are highly variable and may be adjusted to clinical needs. In summary, the proposed FLASHlight MRI method provides a robust acquisition and reconstruction basis for future diagnostic strategies that mimic the usage of ultrasound. Necessary extensions for this vision require remote control of all sequence parameters by a person at the scanner as well as the design of more flexible gradients and magnets.

Keywords: Real-time MRI; interactive MRI; dynamic scanning

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Introduction

A medical tricorder is standard equipment in Star Trek science fiction movies. It allows the user to perform noninvasive and even contactless scans of the human body by moving a small handheld instrument over the tissue or organ of interest while offering detailed biological, chemical and physical information for diagnostic purposes. In principle, current magnetic resonance imaging (MRI) technologies should be able to perform at least part of these tasks with suitable modifications to the imaging process as well as gradient and magnet hardware. Here, we propose first steps towards tricorder-like imaging by describing a solution for the acquisition and reconstruction process which allows for interactive real-time MRI with use of a local receiver coil. At this stage, i.e., within a conventional horizontal-bore MRI system, the handheld coil is freely moveable across the human body while the underlying field-of-view (FOV) and slice position are still controlled from the operating console. Experimental demonstrations comprise dynamic anatomic imaging of the brain, heart, liver and kidney of healthy subjects. Current limitations and necessary extensions are discussed.

Methods

All MRI measurements are performed at 3 T (Magnetom Prisma fit, Siemens Healthineers, Erlangen, Germany) with use of a standard 7 and 11 cm diameter single-turn loop coil or a 4-channel "small flex" coil array of the vendor. Though possible, a combination with elements of the underlying spine coil was deliberately discarded to exclusively explore

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Table 1 Protocols and acquisition parameters for FLASHlight MRI

Parameter	Brain	Thorax, abdomen
Contrast	T2/T1	T1
MRI sequence	Refocused FLASH	Spoiled FLASH
FOV, mm^2	224×224	384×384
Image matrix	298×298	256×256
Resolution, mm^2	0.75×0.75	1.5×1.5
Slice thickness, mm	3.0	6.0
TR/TE, ms	4.76/2.37	2.56/1.58
Spokes per frame	21	13
Flip angle, degree	50	12
Acquisition time per frame, ms	100.0	33.3

MRI, magnetic resonance imaging; FOV, field-of-view; TR, repetition time; TE, echo time.

the potential of handheld receive coils. Subjects without known illness were recruited among the students of the local university. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). Ethical approval was obtained from the ethics committee of the Göttingen University School of Medicine and written informed consent was obtained from all subjects prior to MRI.

FLASHlight MRI is accomplished by highly undersampled radial gradient-echo sequences as previously developed for serial imaging with radial trajectories, for details see (1-4). Radiofrequency excitation involves the body coil, while data acquisition is performed with a receiver coil which may be freely moved across the body—at this stage within a predefined FOV. Depending on the user-selectable parameters of the gradient-echo sequence the proposed method offers access to spin density and T1 contrast for spoiled FLASH with randomized radiofrequency spoiling (5) or to T2/T1 contrast for refocused FLASH or fully balanced steady-state free precessing (SSFP) conditions as controlled by respective gradient switching schemes. Further variants are obtainable by adding interleaved fat suppression (6,7) or spatial pre-saturation modules (8). Extensions based on phase-contrast MRI principles allow for quantitative flow measurements in real time (9-11). Here, the achievable image quality for future diagnostic or interventional imaging scenarios is demonstrated by exemplary anatomic real-time MRI studies of the head, thorax and abdomen. *Table 1* summarizes respective protocols and acquisition parameters.

Serial image reconstructions of FLASHlight acquisitions represent a nonlinear inverse problem. This is because the movement of a receive coil across heterogeneous conductive body tissues is associated with a continuous change of both the image content and the associated coil sensitivity maps. This also applies if multi-coil arrays are replaced by a single-element receive coil. Accordingly, both the desired image and the actual sensitivity map(s) have to be determined for each frame—a task readily accomplished by nonlinear inversion (NLINV) as described (1).

For real-time MRI the radial encoding scheme uses complementary sets of spokes in typically 5 successive frames. This feature improves the regularized nonlinear inverse problem which exploits temporal (or spatial) similarity of neighboring images (1). Post-processing involves a temporal median filter the duration of which matches the number of frames with different sets of spokes. The filter is characterized by retaining “edges”, i.e., relevant signal intensity changes. Its general influence on temporal fidelity and spatial accuracy has been investigated (3). Final image denoising takes advantage of a modified non-local means filter (12).

Because radiofrequency transmission is accomplished by the body coil, FLASHlight MRI is insensitive to potential changes in B1. Alternatively, local transmit-receive coils automatically ensure B1 excitation at the chosen image location. Moreover, the technique does not suffer from B0 inhomogeneities, so that applications not even require

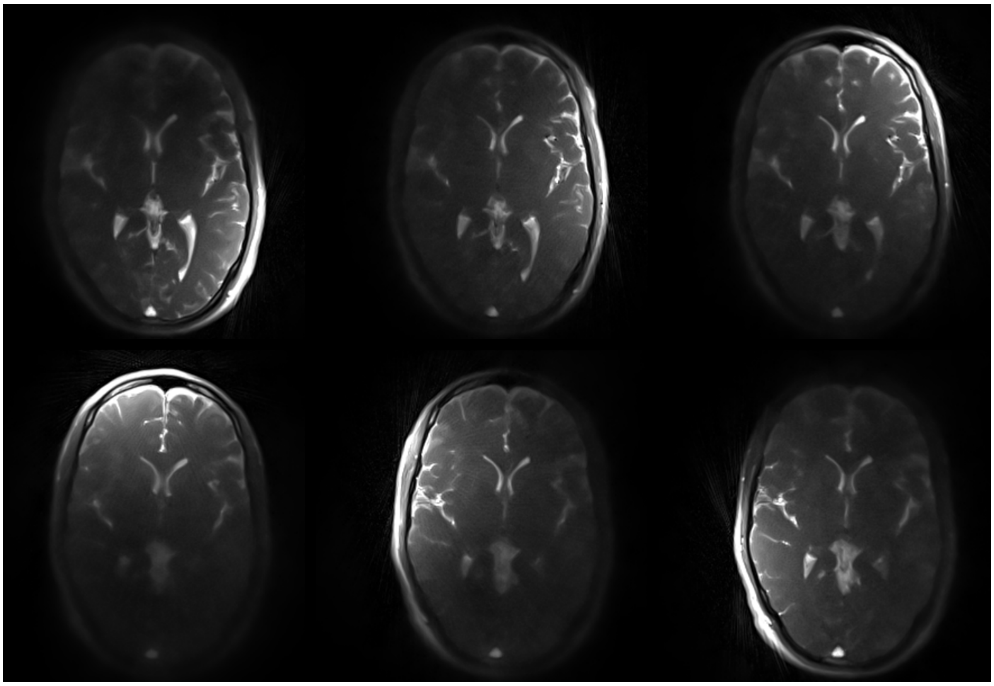
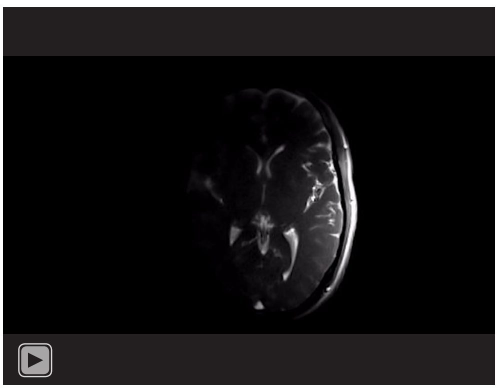


Figure 1 Selected T2/T1-weighted images of a 40 s FLASHlight MRI acquisition (7 cm loop coil) covering the head of a healthy subject at 100.0 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.



Video 1 T2/T1-weighted FLASHlight MRI movie (40 s) covering various positions around the brain of a healthy subject at 100.0 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.

shimming. This is because of the use of high bandwidths and correspondingly short echo times of the radial gradient-echo images.

Online NLINV reconstruction and display of real-time images with negligible latency is achieved with use of a bypass computer (Sysgen, Bremen, Germany) equipped with 4 graphical processing units (NVIDIA V100 SXM2, Santa Clara, CA, USA) and connected to the MRI scanner by a 1 GBit link. Its action is "invisible" to the operator as all sequences are realized in close similarity to vendor protocols and all images are displayed as regular DICOM images on the scanner and stored in the usual databank [for availability see (13)].

Results

The speed and type of movement of the receive coil turned out to be not critical for the NLINV reconstruction which exploits the similarity of the actual image to the previous image. A rapid move of the coil to a distant spot degrades the image quality for only a few intermediate frames before stabilizing again.

Figure 1 and *Video 1* present a FLASHlight MRI study of the human brain at 100 ms temporal resolution. The T2/T1 contrast of the real-time images is a preferred option for diagnostic purposes and obtained by a refocused FLASH sequence. Both the selected frames and the 40 s video demonstrate how the sensitivity of a 7 cm loop coil is shifted within a fixed transverse plane when the subject moves the handheld coil around the head. The images exhibit a steep intensity gradient as their transverse orientation

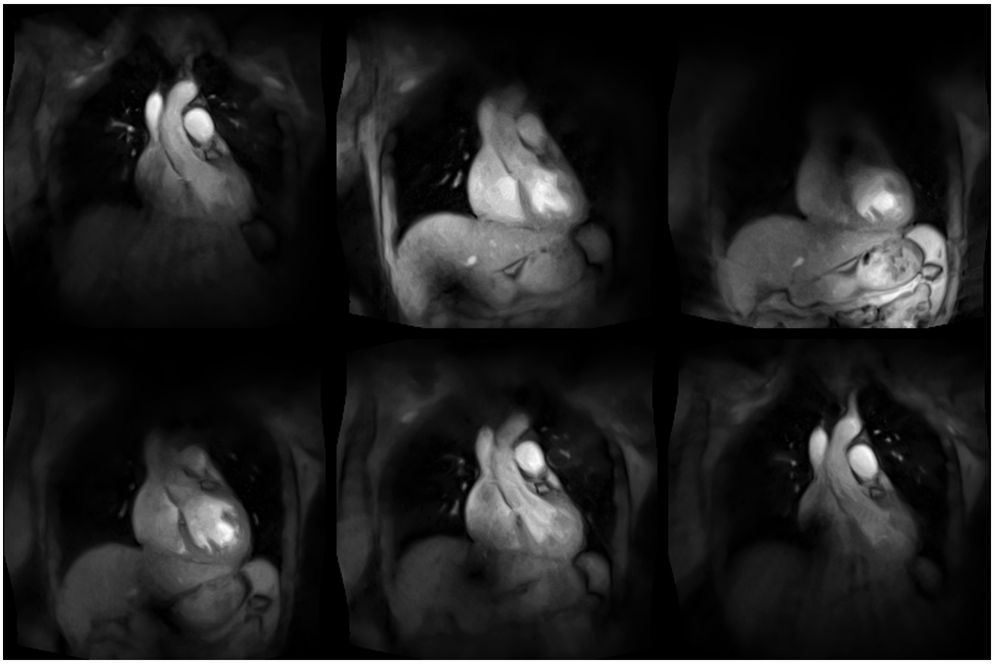
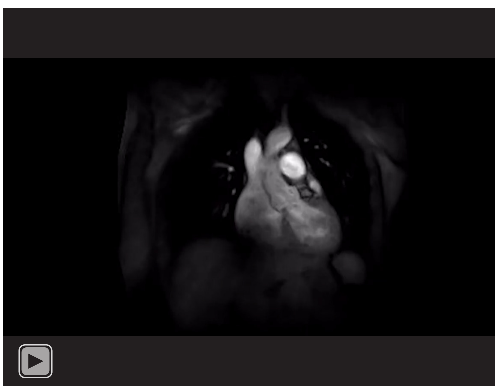


Figure 2 Selected T1-weighted images of a 60 s FLASHlight MRI acquisition (11 cm loop coil) covering the thorax of a healthy subject at 33.3 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.



Video 2 T1-weighted FLASHlight MRI movie (60 s) covering various positions within the thorax of a healthy subject at 33.3 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.

is perpendicular to the plane of the flat surface coil. This situation is different for studies of the thorax and abdomen where the coronal image orientation closely matches the plane of the handheld coil(s). *Figure 2* and *Video 2* highlight the aorta and beating heart with use of a T1-weighted image series at 33.3 ms resolution. The subject moves a handheld 11 cm loop coil atop the thorax along a counter-clockwise trajectory around the heart concomitantly shifting the coil sensitivity within the chosen bulbus view. *Figure 3* and *Video 3* cover the upper abdomen depicting parts of the heart, liver, kidney, spleen and stomach in an oblique coronal plane. In this example, the T1-weighted images at 33.3 ms resolution are acquired with a 4-channel coil array offering an even larger sensitivity field than the 11 cm loop coil.

Discussion

During the past 25 years several attempts have been made to bring MRI into the operating theater, e.g., see a list of selected examples describing software and hardware tools (14-21). The present work complements and extends these ideas by describing an acquisition and reconstruction approach for serial imaging which may serve as a universal and robust solution for the MRI part. To the best of our knowledge, this is the first MRI report about the use of a freely moveable receive coil or coil array, while the underlying real-time MRI technology has been established since more than 10 years and successfully applied in many clinical fields, e.g., see (4,22). The experimental demonstrations represent a proof-of-concept of dynamic

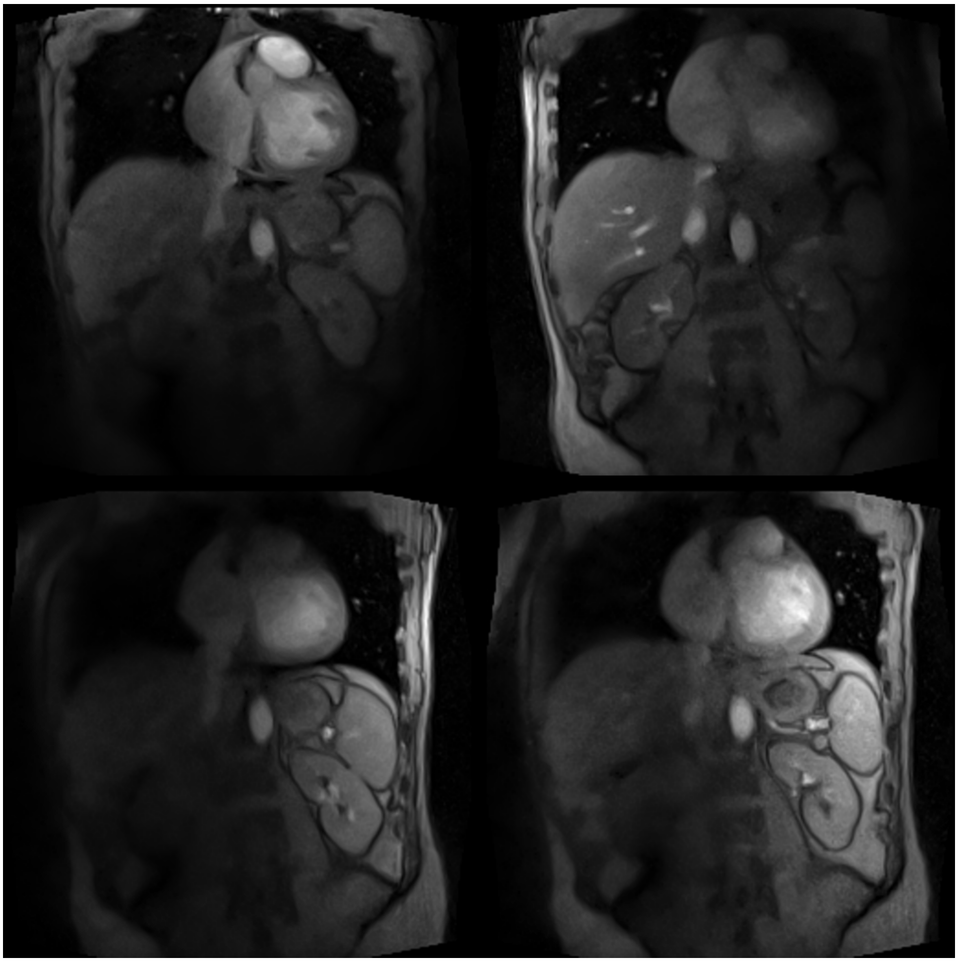
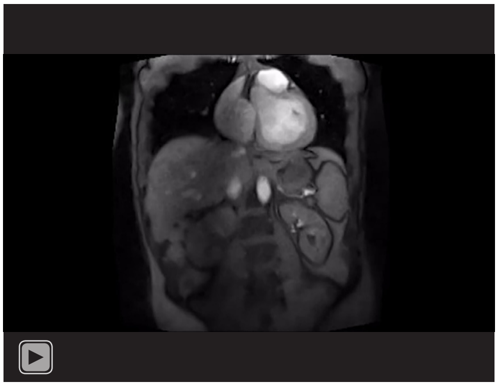


Figure 3 Selected T1-weighted images of a 60 s FLASHlight MRI acquisition (4-channel small flex coil) covering the upper abdomen of a healthy subject at 33.3 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.



Video 3 T1-weighted FLASHlight MRI movie (60 s) covering various positions within the upper abdomen of a healthy subject at 33.3 ms temporal resolution. For further details see *Table 1*. MRI, magnetic resonance imaging.

MRI with a handheld receiver coil which mimics the usage of ultrasound. The results support the notion that recent advances in MRI data acquisition and reconstruction are able to successfully treat the acquisition and reconstruction problem encountered in future interactive MRI scenarios. Of course, FLASHlight MRI represents only one of many elements required for dealing with the entire process (see below), but it solves the MRI part and hence brings us closer to the vision of a functioning "medical tricorder".

The approach promises a variety of potential applications and technical variants that need to be examined. Once flexible open-structured MRI hardware becomes available FLASHlight MRI will allow for interactive real-time monitoring of interventional procedures such as a biopsy with optimized signal-to-noise ratio and spatiotemporal resolution. The method is also expected to simplify the investigation of speech and swallowing processes as well as of movements of the temporomandibular joint, shoulder, hand, knee and foot. Studies are easily extended to musculoskeletal problems (e.g., arm, thigh, and leg) and abdominal questions (e.g., small bowel and prostate). Moreover, foreseeable extensions include fetal imaging. On the technical side further developments range from the use of transmit-receive coils to flow analyses based on velocity-encoded phase-contrast MRI. At this stage the straightforward extension to real-time flow MRI is already possible but slightly too slow for interactive real-time applications. This is because the preferred methodology (9-11) is based on a model-based reconstruction technique, which directly estimates the anatomic image and corresponding velocity map from the two flow-encoded datasets and therefore avoids any phase subtraction and associated salt-and-pepper noise in image parts without MRI signal support. Though accelerated via graphical processing unit (GPU) implementation the online reconstruction speed for real-time flow MRI does not yet fully reach the typical FLASHlight speed of 10 to 30 fps.

So far, all FLASHlight MRI demonstrations employed a single cross-sectional slice. However, the technique allows for simultaneous multi-slice acquisitions both in parallel and orthogonal orientations. Although at the expense of temporal resolution, slice-interleaved acquisitions maintain the same temporal footprint (i.e., acquisition time) and thus avoid temporal blurring. In fact, even volumetric scans are possible with use of a novel method for rapid volume coverage that exploits the same NLINV reconstruction as for dynamic real-time MRI (23). It relies on a cross-sectional real-time acquisition where the slice position of each frame is automatically shifted by a certain percentage of the slice thickness. Such motion-robust volumetric scans take only a few seconds and may be an option for repetitive scanning of a target tissue.

The current implementation suffers from several limitations. First of all, the used MRI system is a regular horizontal-bore scanner without any equipment for remote control of sequence parameters. This particularly refers to a dynamic change of the FOV in order to enhance the spatial resolution or a change of image contrast at a target spot. More general restrictions that need to be overcome in order to accomplish ultrasound-like (or Star Trek-like) MRI diagnostics or interventions comprise a variety of hardware elements. These include local gradient coils as well as open or even portable magnet structures, eventually based on novel high-temperature superconducting materials. In principle, individual technologies are already available, but it remains to be seen how to bring these elements together.

In summary, the proposed FLASHlight MRI technique provides a robust acquisition and reconstruction basis for future diagnostic strategies that allow for tricorder-like MRI scanning.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://qims.amegroups.com/article/view/10.21037/qims-22-648/coif). DV and JF report that they are co-inventors of a patent describing the MRI method used here. The other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). Ethical approval was obtained from the ethics committee of the Göttingen University School of Medicine and written informed consent was obtained from all subjects prior to MRI.

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