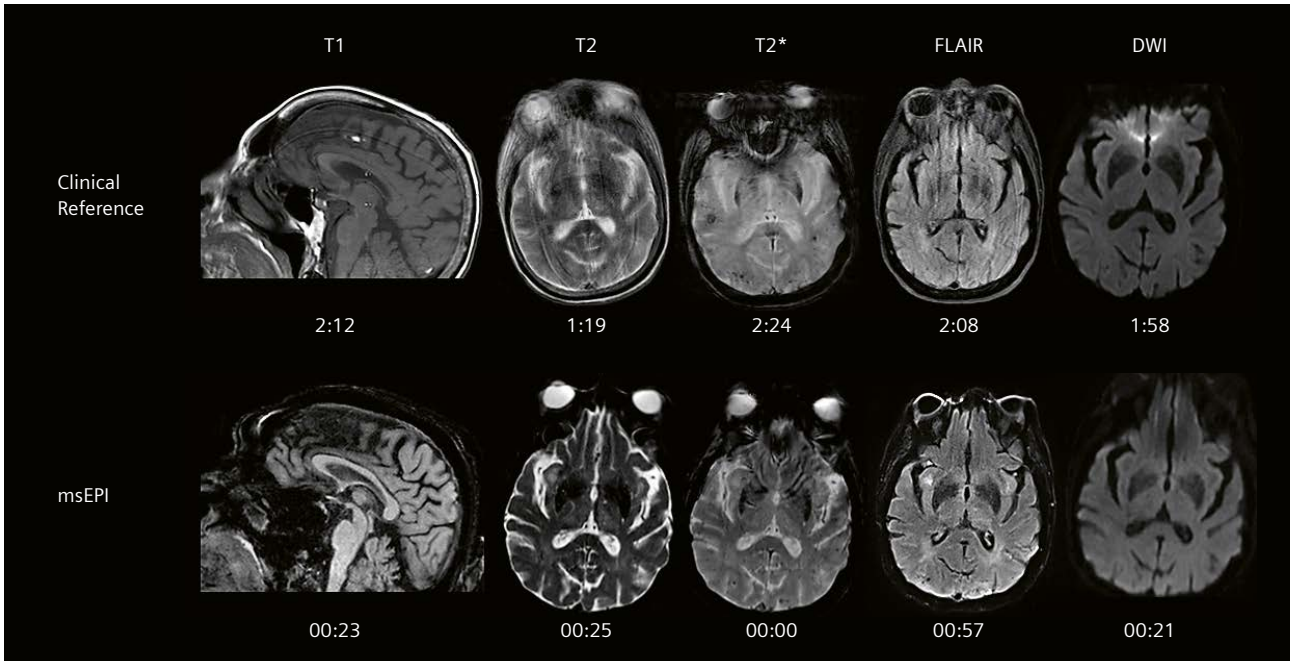
Ultrafast Brain Imaging with Deep Learning Multi-Shot EPI: Preliminary Clinical Evaluation

Azadeh Tabari[1], Bryan Clifford[2], Augusto Lio M. Goncalves Filho[1], Zahra Hosseini[3], Thorsten Feiweier[4], Wei-Ching Lo[2], Min Lang[1], Maria Gabriela Figueiro Longo[1], Kawin Setsompop[5], Berkin Bilgic[6], Otto Rapalino[1], Pamela Schaefer[1], Stephen Cauley[6], Susie Huang[1], John Conklin[1]

[1]Department of Radiology, Massachusetts General Hospital, Boston, MA, USA
[2]Siemens Medical Solutions USA, Boston, MA, USA
[3]Siemens Medical Solutions USA, Atlanta, GA, USA
[4]Siemens Healthineers, Erlangen, Germany
[5]Department of Radiology / Department of Electrical Engineering, Stanford University, Stanford, CA, USA
[6]Department of Radiology, A. A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA

MR imaging (MRI) is an integral part of the diagnosis and treatment planning of various neurological diseases. However, the long scan time of brain MRI is a major factor that limits its effectiveness, especially in patients who are prone to motion and frequently require sedation. Thus, fast brain MRI protocols with acceptable diagnostic image quality are desired to enable wider clinical application of MRI [1, 2]. There is an ongoing clinical need to reduce the scan time of brain MRI, especially for uncooperative or motion-prone patients, and patients with diseases requiring rapid diagnosis such as stroke.

Various efforts have been made to achieve ultrafast MRI for brain imaging by using pulse sequences that rapily acquire images. One well-known approach is to use



1 Illustrative example on the comparison of the motion-degraded exam of a 10-minute clinical reference protocol to the proposed 2-minute msEPI protocol in a 73-year-old female with no pathologic findings.

single-shot echo-planar imaging (ssEPI), which acquires *k*-space data for an entire 2D image in a single, long readout (shot), following a single RF-excitation pulse [3, 4]. The number of *k*-space lines (echoes) collected in a single shot is called the "EPI factor". The technical advances in the design of echo-planar imaging have made ultrafast brain MRI protocols, including a combination of anatomic and functional sequences, possible [5, 6]. ssEPI methods have recently been used to create rapid screening exams with total durations of 1–2 minutes. However, these rapid ssEPI approaches come at the cost of significant geometric distortion, low signal-to-noise ratio (SNR), and reduced tissue contrast [6–8]. In addition, these approaches offer limited flexibility to acquire in different image orientations or to repeat individual contrasts.

Multi-shot EPI (msEPI) acquisitions have been exploited to address these shortcomings. In a msEPI acquisition, data from multiple highly-undersampled shots are combined together. This approach results in reduced geometric distortion, but at the cost of slightly longer scan times. Higher acceleration factors can be used to compensate for this, but can lead to increased *g*-factor noise and residual aliasing [9–11]. Recent advancement in artificial intelligence (AI)-powered reconstruction algorithms have proved successful in denoising accelerated MRI data. Deep learning (DL) models, can be applied to reduce noise and residual aliasing during reconstruction [12].

In this article we show preliminary results from a clinical translational study being performed at Massachusetts General Hospital (MGH) for validating the feasibility of prototype DL-accelerated msEPI-based rapid brain protocols[1] in a high-volume emergency and inpatient care setting. The rapid imaging technique combines a novel deep learning algorithm to limit *g*-factor noise amplification, magnetization transfer preparation to improve brain tissue contrast, and high per-shot EPI undersampling factors to minimize geometric distortion [12, 13]. A multidisciplinary team of neuroradiologists, MR physicists, and Siemens Healthineers engineers at MGH have developed and optimized acquisition parameters for each of these prototype msEPI-based MRI protocols. Following the optimization of sequence parameters and DL-based reconstruction, an Institutional Review Board approved study was executed. The validation approach comprised prospective comparative studies of emergency and inpatient examinations with a variety of indications. The imaging protocol included T1-, T2-, T2*-weighted, T2-FLAIR, and DW imaging sequences from the prototype msEPI protocol and the clinical reference standard. Imaging was performed on 3T MRI scanners (MAGNETOM Skyra and MAGNETOM Prisma, Siemens Healthcare, Erlangen, Germany) using a 20-channel head coil. Fully sampled msEPI training data were acquired with two averages and eight shots across 16 healthy subjects (8 men, 8 women, aged 19–67). A single FLASH auto calibration scan, acquired at the start of each acquisition, allowed for the calculation of coil sensitivity maps, GRAPPA and/or SMS kernels. The data were split into training and validation datasets with 12 and 4 subjects, respectively. The use of fully sampled data allowed networks to be trained for different acceleration factors through retrospective undersampling.

Two board-certified neuroradiologists, blinded to the clinical history and the imaging protocols, evaluated the head-to-head image quality, scan time, and diagnostic performance of DL-accelerated msEPI-based MRI protocols against the respective clinical standard protocols. For diagnostic performance, they assessed six clinically relevant imaging findings in each protocol (intracranial mass-like lesion, intracranial hemorrhage, white matter hyperintensities, subarachnoid FLAIR hyperintensities, diffusion restriction, and hydrocephalus). For image quality, the raters used a 3-point score to evaluate image degradation by noise and artifacts. Qualitative assessment was compared using Wilcoxon signed-rank tests, and the intraclass correlation coefficients (ICCs) were used to test interobserver reproducibility on the diagnostic concordance between two readers.

Initial clinical experience

The prototype msEPI protocols (T1-, T2-, T2*-weighted, T2-FLAIR, and DWI) required only 2 minutes of scan time (not including adjustments), while the rapid reference protocols (turbo spin-echo (TSE)-based acquisitions) took 10 minutes for the same number of image contrasts. A total of 26 patients (Male:Female 12:14, mean age 58 ± 19 years old) were included in this preliminary study.

Two board-certified neuroradiologists performed an initial clinical subjective evaluation of the DL-accelerated msEPI-based images. Aside from noticeable mild distortion of soft facial tissues, the msEPI images contained only very minimal distortion of the pons and temporal lobes – areas which are critical for diagnosis. The limited artifacts we observed were most prevalent in the longer echo-time T2* data and corresponded to cases where patient motion could be identified. Figure 1 illustrates how shorter scan time allows for lower motion artifacts.

Interobserver agreement was 'almost perfect' for the evaluation of intracranial masses (ICC = 1), WM hyperintensities (ICC = 0.83), diffusion restrictions (ICC = 0.83), and hydrocephalus (ICC = 1); and 'substantial' for intracranial hemorrhage (ICC = 0.76) and subarachnoid FLAIR

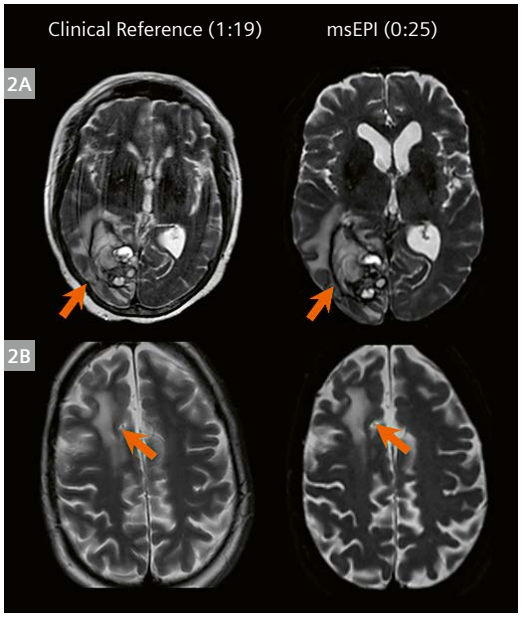
[1] *Work in progress. The application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

hyperintensities (ICC = 0.65). Head-to-head comparisons of image quality showed increased noise on the msEPI exams for T1, FLAIR, and DWI ($p < 0.05$) and increased artifacts on T2, T2*, and FLAIR ($p < 0.05$), without compromising the detection of the imaging findings.

Figures 2–6 demonstrate examples of the msEPI images and the corresponding clinical reference images for each image contrast, highlighting the clinical findings in each. As these cases illustrate, the 2-minute DL-accelerated msEPI prototype sequences can offer high clinical efficacy at a significantly shorter acquisition time.

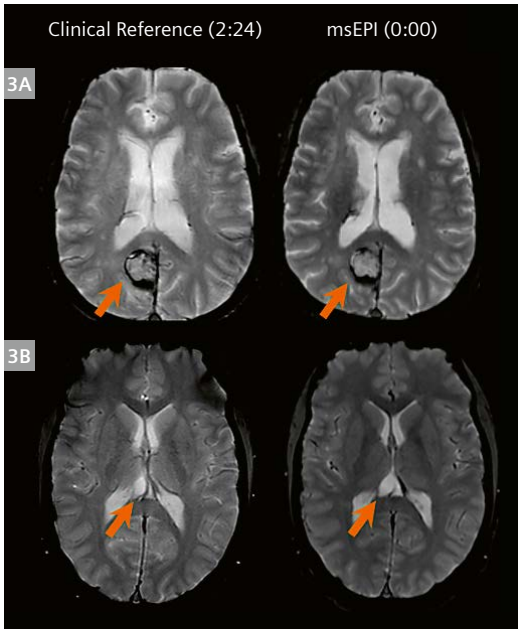
Conclusion

We have successfully used a DL-accelerated 2-minute msEPI protocol to enable rapid, comprehensive brain MRI evaluation of emergency department and hospitalized patients. In this preliminary study we found high interobserver agreement for major brain MRI findings, similar to that of a 10-minute conventional protocol. The DL-accelerated 2-minute msEPI protocol provided clear depiction of pathologic intracranial findings and comparable tissue contrast to that observed with the five-fold slower clinical reference exam. The msEPI technique is currently being evaluated in a larger clinical study of inpatient and emergency department patients at our institution, which



T2 Sequence	Acquisition Time (m:s)	Resolution (mm^3)	TR (ms)	TE (ms)	PAT Factor	No. shots	Echo spacing (ms)
TSE	1:19	0.9×0.9×5.0	7060	85	2	–	9.42
msEPI	0:25	1.0×1.0×4.0	4500	86	2	4	1.2

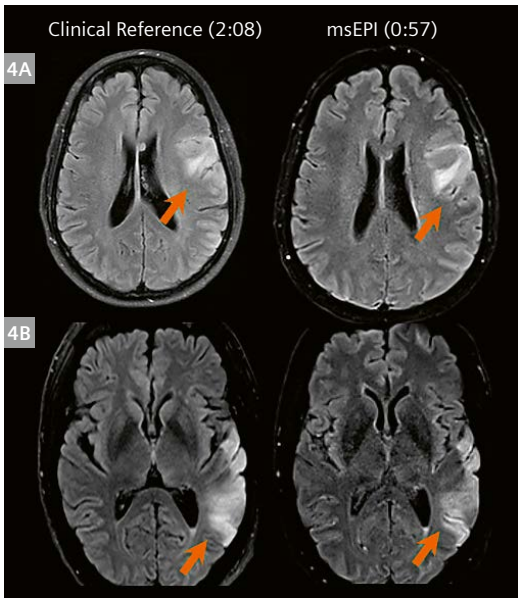
2 **(2A)** Large complex hemorrhagic mass-like lesion within the right occipital lobe that is better seen on msEPI exam. The clinical reference exam that was performed with > 3-fold increase in scan time demonstrates intense motion artifacts.
(2B) Post-surgical changes from right frontal craniotomy with right frontal lobe encephalomalacia.



T2* Sequence	Acquisition Time (m:s)	Resolution (mm^3)	TR (ms)	TE (ms)	PAT Factor	No. shots	Echo spacing (ms)
GRE	2:24	0.9×0.9×5.0	694	20	1	–	–
msEPI	0:00[2]	1.0×1.0×4.0	4500	21.2	2	4	1.2

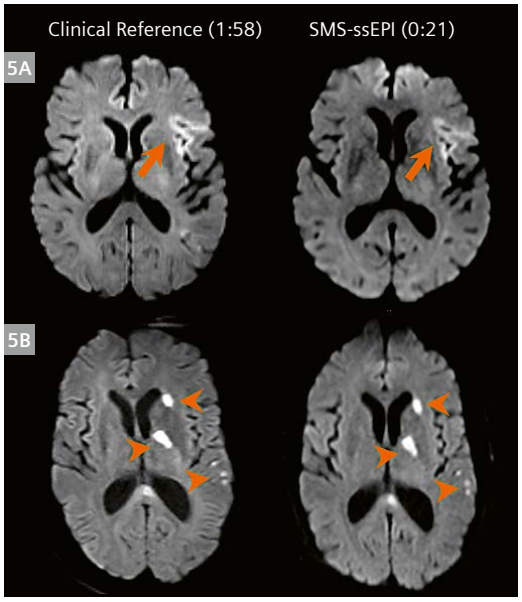
3 **(3A)** Right parietal lobe intraparenchymal hematoma with dependent T2* hypointense blood products.
(3B) Non-enhancing cystic lesion in the right aspect of the pineal gland.

[2] *Acquired in combination with the T2 sequence.*



FLAIR Sequence	Acquisition Time (m:s)	Resolution (mm³)	TR (ms)	TE (ms)	PAT Factor	No. shots	Echo spacing (ms)
TSE	2:08	0.9×0.9×5.0	9000	85	2	–	7.49
msEPI	0:57	1.0×1.0×4.0	9000	86	2	2	1.19

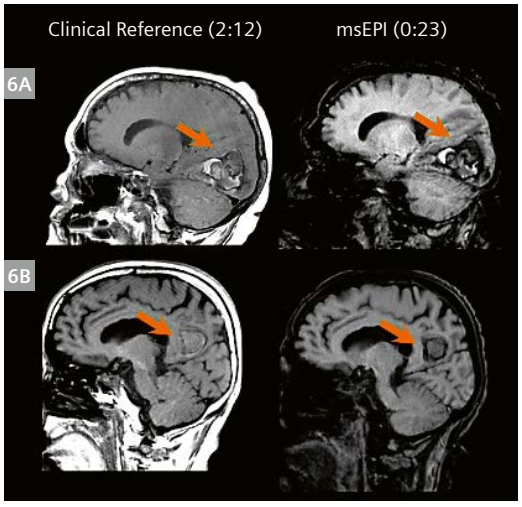
4 **(4A)** Left frontal high-grade glioma.
(4B) Subacute left temporal lobe infarct (left middle cerebral artery territory).



DWI Sequence	Acquisition Time (m:s)	Resolution (mm³)	TR (ms)	TE (ms)	PAT Factor	No. shots	Echo spacing (ms)
ssEPI	1:58	1.4×1.4×5.0	3800	72	2	1	0.72
SMS-ssEPI	0:21	1.4×1.4×4.0	2000	63	2	2	0.93

b-value 1000 s/mm²

5 **(5A)** Subacute infarct involving left frontal lobe and insula.
(5B) Multiple infarcts involving left cerebral hemisphere.



T1 Sequence	Acquisition Time (m:s)	Resolution (mm³)	TR (ms)	TE (ms)	PAT Factor	No. shots	Echo spacing (ms)
SE	2:12	0.9×0.9×4.0	400	8.4	1	–	–
msEPI	0:23	1.0×1.0×4.0	1670	12	2	4	1.18

6 **(6A)** Hemorrhagic neoplastic lesion in the right occipital lobe.
(6B) Right parietal lobe intraparenchymal hematoma.

will provide further insight into the advantages and trade-offs of ultrafast, high-quality brain imaging in this patient population. We envision this protocol could be an effective rapid screening tool for acute intracranial pathology in these often difficult to image and neurologically unstable patients.

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Contact

John Conklin, M.D., MS
Diagnostic Radiologist
Director of Emergency MRI,
Division of Emergency Imaging
Department of Radiology
Massachusetts General Hospital
326 Cambridge St #410
Boston, MA 02114
USA
Phone: +1617-726-8323
John.Conklin@MGH.HARVARD.EDU