Brain ultrasound imaging with diffusion-guided full waveform inversion

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Background

Fast and accurate brain imaging is critical for the detection and **treatment of stroke,** especially in acute cases where treatment decisions must be made within minutes. However, whilst current imaging technology such as magnetic resonance imaging (MRI) and computed tomography (CT) can provide high-resolution images, both have major limitations: both require patients to be transferred to hospital, losing valuable time, MRI scans are slow, impractical and expensive, and CT exposes patients to ionising radiation.

Imperial is developing a portable, radiation-free, and high-resolution alternative; **transcranial ultrasound full-waveform inversion** (FWI) imaging [1]. This technology works by using transducers to send sound waves into the brain and processing the transmitted and reflected signals to construct an image. Crucially, this only requires a helmet to be worn (Figure 1), allowing scans to be taken on location minutes after a stroke.

Unlike conventional ultrasound, which relies on simplified beamforming techniques, FWI imaging works by solving the full wave equation, iteratively updating a velocity model of the brain to match measured waveforms. This algorithm is capable of delivering sub-millimetre 3D reconstructions with superior soft-tissue contrast compared to CT imaging [1]. However, in practice FWI faces significant challenges that limit its clinical utility. The imaging problem is severely **ill-posed**: sparse transducer coverage, measurement noise, limited frequency content, and skull-soft tissue scattering make it extremely challenging to uniquely determine the underlying velocity model of the brain, which often leads to poor image quality. Furthermore, each iteration of FWI requires solving the wave equation, making it computationally expensive for real-time applications.

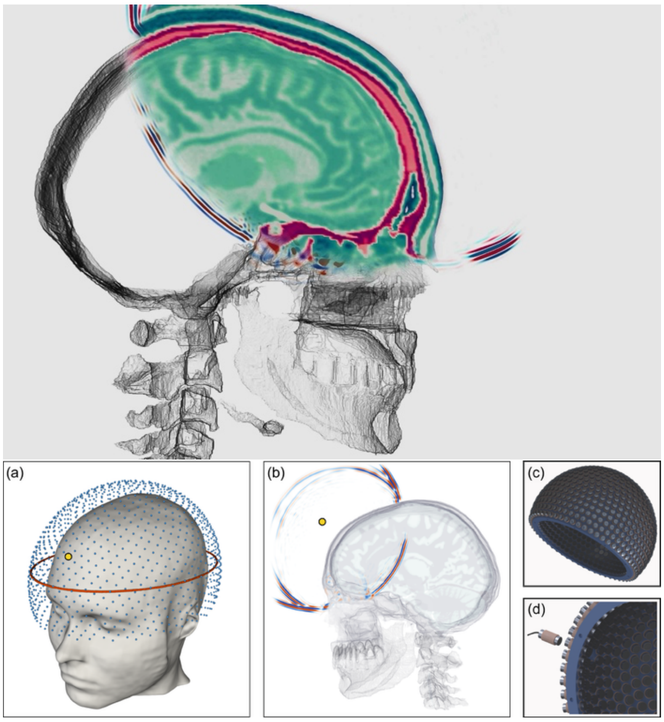

Figure 1: Ultrasound full-waveform inversion (FWI) imaging of the brain (top), and our prototype helmet images the brain (bottom) [1].

Project

In this project, we will investigate using AI to **improve the accuracy and efficiency** of the FWI algorithm, improving its reconstructed image quality. Our recent work has shown that **diffusion models**, state-of-the-art generative ML techniques often used for image generation, can help FWI converge to the true velocity model [2]. Specifically, we trained a diffusion model to generate brain images and then used its generative process inside the FWI algorithm to help guide FWI towards a realistic image, similar to [3]. We found that this **helped the FWI algorithm converge** in ill-posed settings, for example with sparse transducers and limited frequency content in the sound waves.

This project will **take this proof-of-principle work to the next step**; training robust diffusion models which are able to generate exceptionally high resolution and diverse 3D brain images, thoroughly investigating how best to incorporate the diffusion model into the FWI algorithm to improve performance, studying whether this workflow allows real-time imaging, and working with our hardware team to improve helmet design based on our findings.

Key research questions are: Can diffusion models generate high-resolution and anatomically realistic brain images? How should diffusion priors be incorporated into FWI to improve convergence? Can AI-augmented FWI reduce computation enough for real-time imaging? How can FWI insights inform helmet design and transducer placement? How robust is the approach to noise, sparse data, and patient variability?

Impact

This project has the potential to transform stroke diagnosis and treatment by enabling rapid, portable, and radiation-free brain imaging at the point of care. By combining advanced ultrasound FWI with AI, we aim to overcome current barriers of image quality and speed, paving the way for real-time, high-resolution imaging in emergency settings. Beyond stroke, the methods developed could influence broader medical imaging, inform hardware design, and establish new AI-driven approaches to solving ill-posed inverse problems in healthcare and beyond.

Supervisory team

Dr. **Ben Moseley** is an Assistant Professor in AI (Schmidt AI in Science Fellow) at the Department of Earth Science and Engineering and a Fellow at the Imperial I-X Centre. He heads the Scalable Scientific Machine Learning Lab and is an expert in scientific machine learning, physics-informed neural networks, neural differential equations, hybrid modelling, learned inverse algorithms, high-performance computing, geophysics, and planetary data science.

Dr. **Carlos Cueto** is an Assistant Professor in AI and Fluid Flow Imaging at the Department of Earth Science and Engineering (ESE). He is an expert in computational modelling and imaging, high-performance computing, and machine learning applied to medical and geophysical imaging. He leads the Stride project, an open-source library for high-performance FWI imaging and its integration with machine-learning models. He is module lead for the Deep Learning course in ESE's Ada Lovelace Academy.

Dr. **Debbie Pelacani Cruz** is a Teaching Fellow in the Department of Earth Science and Engineering (ESE), where they research AI-aided ultrasound brain imaging and AI for education. They recently completed a PhD specialising in generative models and currently teach Deep Learning and Inversion & Optimisation on ESE's postgraduate programmes.

Dr. **Oscar Calderón Agudo** is an Advanced Research Fellow (UKRI Future Leaders Fellow) at the Department of Earth Science and Engineering (ESE). He leads the Transmission and Reflection Ultrasound (TRUST) research group to develop high-resolution wave-based imaging algorithms, devices and technologies. He originally conceived and developed the core technology for FWI transcranial imaging, is a co-founder of Sonalis Imaging Ltd, and Enterprise Champion for the ESE Department.

Student profile

We are looking for a motivated student to pursue a PhD at the intersection of scientific machine learning, medical imaging, and high-performance computing. This is an interdisciplinary project, and we do not expect candidates to arrive with expertise in all areas; instead, we are looking for someone with a strong technical foundation, enthusiasm for interdisciplinary research, and an ability to approach complex problems with creativity and curiosity.

Essential qualifications / experience:

- Good Master's degree in a relevant field (e.g. applied mathematics, physics, computer science, engineering, or related areas). Motivated candidates with an excellent bachelor's degree and a relevant research portfolio are encouraged to apply
- Completed courses in machine learning and/or applied mathematics
- Coding proficiency in e.g. Python/ C++/ Julia/ Fortran

Desirable qualifications / experience:

- Experience in numerical modelling (finite difference, finite element, spectral methods, etc)
- Experience training generative ML models
- Experience in seismic/ultrasound imaging or other relevant inverse problems
- Proficiency with Python machine learning frameworks (PyTorch, JAX (with Equinox))
- Experience in scientific, HPC, GPU, and/or parallel computing
- Relevant publications and/or industry experience are a plus

Funding

This project is not currently funded through a research grant and is eligible for College and/or Departmental scholarship funding. For more details on scholarship funding and deadlines see here.

Apply

If you are interested, please start by sending us:

- CV (including education, and any research experience).
- Brief motivation letter (200 – 400 words) where you should highlight how your experience enables you to pursue the project (can be in the email body).
- Any additional materials that support your application (optional).

For more details on the Imperial PhD application process see here.

Contact

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References

[1] Guasch, L., Calderón Agudo, O., Tang, M. X., Nachev, P., & Warner, M. (2020). Full-waveform inversion imaging of the human brain. Npj Digital Medicine.
[2] Horanieh, M., Li, J., (2025). Imperial MSc project: Diffusion models and ultrasound full-waveform inversion (contact us for more info).

[3] Song et al, Solving Inverse Problems in Medical Imaging with Score-Based Generative Models, ICLR (2022).