



Spectral coupling of arteriovenous fistula sound and flow-induced wall vibrations

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ABSTRACT

A native arteriovenous fistula (AVF) is the preferred vascular access for connecting a patient's circulation to a haemodialysis machine, but it can fail due to adverse vascular remodelling. AVFs produce characteristic sounds, likely generated by flow-induced high-frequency vessel wall vibrations.

The aim of this study was to provide evidence of the relationship between AVF sounds and computed flow-induced wall vibrations, through a multi-domain characterisation of AVFs that integrated acoustic analyses and fluid structure interaction (FSI) simulations.

Spectrograms of recorded AVF sounds from four patients showed frequency content comparable to FSI-derived vascular wall vibrations. This spectral coupling suggests that sound analysis could serve as a simple, non-invasive tool for early detection of AVF dysfunction.

1. Introduction

Although a native arteriovenous fistula (AVF) is the preferred vascular access for connecting a patient's blood circulation to a haemodialysis machine, it is associated with a rate of failure of up to 40 % within the first year after surgical creation, primarily due to stenosis of the AVF vein (Bozzetto et al., 2022).

In clinical practice, physicians and nurses routinely perform physical examinations of the AVF, including assessment of the thrill and auscultation of the associated sounds, as qualitative monitoring techniques. Based on their experience, they have learned to distinguish between the sounds of well-functioning and stenotic AVFs (Lok et al., 2020). Building on this expertise, recent studies using electronic stethoscopes for AVF auscultation have quantified characteristic acoustic signatures that differ between well-functioning and failing fistulas, the latter being characterised by higher frequency contents (Chang et al., 2026; Poloni et al., 2025).

At the same time, we have shown through patient-specific image-based fluid structure interaction (FSI) simulations that transitional blood flow induces high-frequency vascular vibrations in the AVF wall

(Bozzetto et al., 2024). Furthermore, we have suggested, in a longitudinal case study, that AVF wall vibrations are spatially and temporally associated with stenosis formation (Soliveri et al., 2025), meaning that they are predominantly located in vascular regions that later developed stenosis and which intensify right before stenosis development, potentially acting as a mechanobiological stimulus for AVF stenosis.

Despite the potential of AVF sounds for clinical monitoring and the preliminary evidence of AVF wall vibrations' involvement in stenosis development, AVF sounds and wall vibrations have so far been investigated independently. We hypothesise that the audible sounds that enable non-invasive AVF monitoring arise from the propagation, through surrounding tissues, of vascular wall vibrations induced by flow instabilities. Therefore, the aim of the present study is to provide evidence of the relationship between AVF sounds and computed flow-induced wall vibrations, through a multi-domain characterisation of AVFs integrating acoustic analyses and FSI computational modelling.

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2. Materials and methods

2.1. Study design

The data used for this analysis were collected as part of the RESHAPE clinical study (NCT04141852), approved by the local ethics committee (Reg. n. 107/19), for which all patients provided informed consent. Specifically, we included in the present analysis only a subset of the overall dataset: four patients at the time of functional maturation, defined as the first use of the AVF for haemodialysis treatment. During a single visit, patients underwent AVF sounds recording by an electronic stethoscope, contrast-free magnetic resonance imaging (MRI) and Doppler ultrasound examinations, used as input to perform patient-specific FSI simulations (see the workflow in Fig. 1). Acoustic recordings and computational data were then processed, and results compared to investigate the relationship between AVF sounds and computed AVF wall vibrations.

2.2. AVF sound recording and analysis

Acoustic signals from AVFs were recorded at the anastomosis site using a 3 M Littmann 3200 Electronic Stethoscope, with each acquisition lasting for at least five seconds. Recordings were acquired in extended-range mode to cover the frequency band of interest. For each patient, AVF sounds were recorded under quiet conditions to reduce environmental noise, taking care to avoid skin friction and excessive pressure on the AVF, which could have altered the recorded signals.

The audio files of AVF sounds were transferred to a computer via Bluetooth through the stethoscope's dedicated application. Pre-processing was carried out in Python by selecting a single cardiac cycle for each recording and applying a high-pass filter at 25 Hz. Spectrograms of AVF sound were subsequently generated.

2.3. FSI simulation

The complete FSI pipeline used in this study has been described in detail in previous papers (Soliveri et al., 2024; Yamamoto et al., 2025). Specifically, the computational parameters used here are the same as those reported by Soliveri et al. (2024). Briefly, contrast-free MRI scans were acquired using a 1.5 T scanner, covering a region that extended 5 cm upstream and 3 cm downstream of the anastomosis. Three-dimensional AVF surfaces obtained from the MRI images were used to generate meshes with $\sim 200,000$ tetrahedral elements. FSI simulations were performed using the turtleFSI solver, a monolithic, space/time-centred method that is second-order accurate in time and uses quadratic finite elements in space. Specifically, quadratic (P_2) elements

are employed for solid deformation and velocity, while linear (P_1) elements are used for pressure. A time step of 0.1 ms was adopted to resolve high-frequency velocity and pressure fluctuations. Patient-specific flow waveforms from Doppler ultrasound were imposed at the proximal and distal radial artery inlets. Distinct arterial and venous material properties were incorporated. The mechanical effect of the perivascular environment on the vessel wall was modelled via a viscoelastic spring-dashpot system. Simulations were run for three cardiac cycles (3 s), but only the last cycle was used for post-processing to avoid initial transients from the simulation setup.

The Q-criterion at systolic peak was applied to identify vortical structures and flow instabilities. Data were high-pass filtered at 25 Hz and spectrograms of blood flow velocity, pressure at the interface between fluid and solid domains, and vascular wall displacement were computed at the anastomosis and first tract of the vein to assess their frequency content.

3. Results

Spectrograms of recorded AVF sounds showed a frequency content comparable to FSI-derived vascular wall vibrations, as shown in Fig. 2 (left and right panels). Specifically, AVF1 and AVF4 showed distinct high-amplitude frequency bands in the range of 50–200 Hz, while AVF2 exhibited a higher frequency content up to 500–600 Hz, in both acoustic and vascular wall displacement spectrograms. In AVF3, although both the AVF sound and the vessel wall displacement spectrograms exhibited a main frequency band of around 50 Hz, the FSI-derived spectrum also showed high-amplitude frequency bands of up to 650 Hz, which appeared nearly invisible in the AVF sound spectrogram.

The heterogeneous frequency signatures of FSI-derived vessel wall displacement (Fig. 2, right panel) are consistent with the different hemodynamic phenotypes shown by the Q-criterion and the velocity and pressure spectrograms (Fig. 2, mid panel). Indeed, AVF1 and AVF4 were characterised by a more stable flow phenotype with low frequencies in the fluid velocity and interface pressure spectrograms. On the contrary, AVF2 and AVF3 showed vortex and oscillations in blood flow, that were clearly visible in the representation of the Q-criterion, corresponding to higher frequencies in the spectrograms of the fluid velocity and of the interface pressure.

4. Discussion

This study shows that there is a relationship in the spectral frequency content of AVF sound recordings and FSI-derived AVF wall vibrations. Specifically, recorded AVF sounds show distinct high-amplitude frequency bands, which correspond to those contained in the FSI-derived

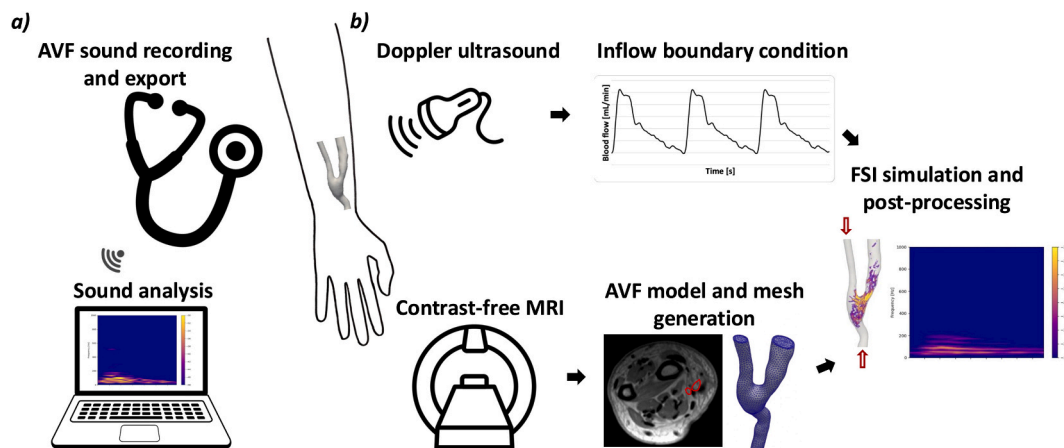


Fig. 1. AVF multi-domain characterisation workflow. a) AVF acoustic recording and analysis; b) FSI computational modelling pipeline. Abbreviations: AVF = arteriovenous fistula; FSI = fluid–structure interaction; MRI = magnetic resonance imaging.

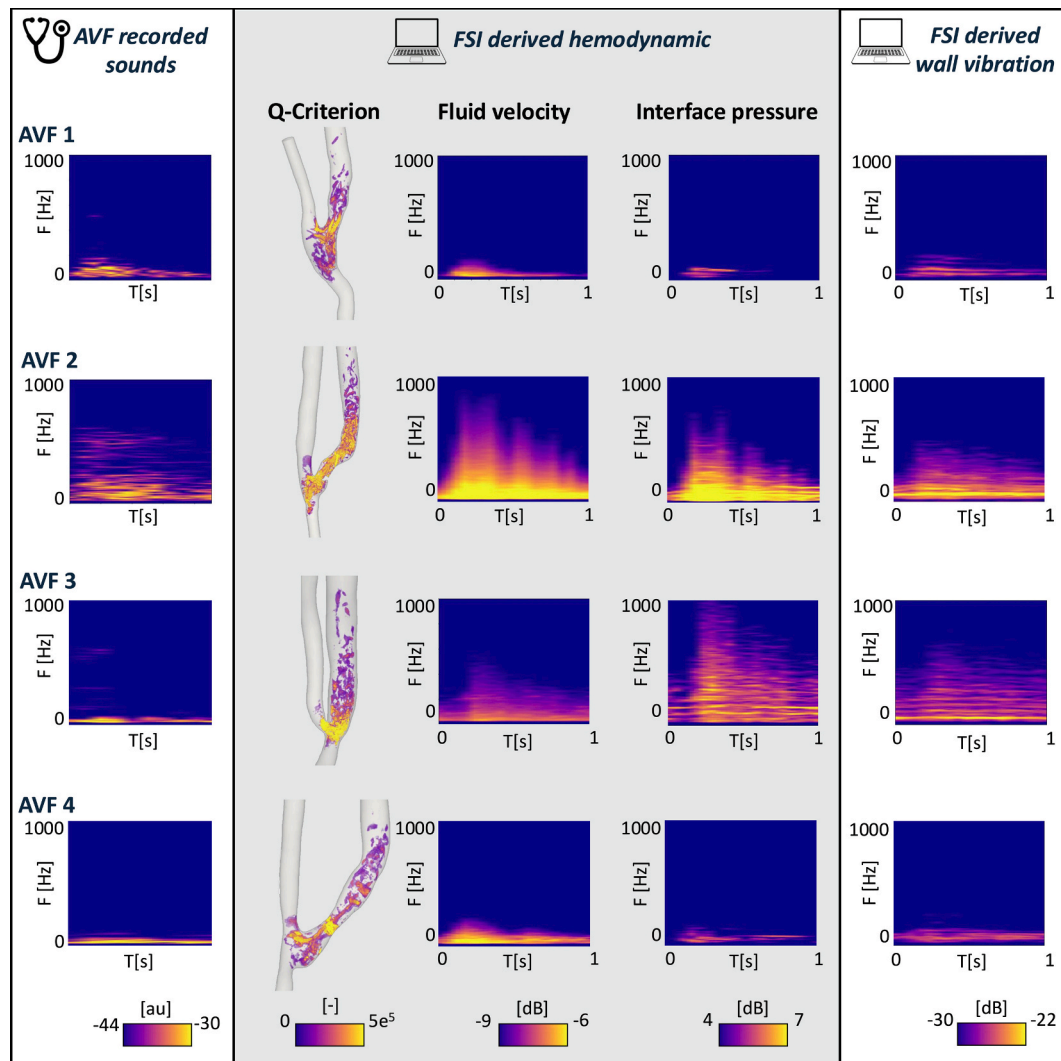


Fig. 2. Multi-domain characterisation of the AVFs of the four patients included in the investigation. Each row corresponds to a different AVF (1–4). The left panel displays spectrograms of AVF sounds recorded by an electronic stethoscope. The mid shadowed panel shows the results of FSI simulations, namely vortex visualisations (Q-Criterion) and spectrograms of fluid velocity and interface pressure. The right panel displays vessel wall displacement spectrograms obtained from FSI simulations. Abbreviations: AVF = arteriovenous fistula; FSI = fluid–structure interaction.

spectrograms of the vascular wall displacement.

The presence of high-frequency spectral bands in the measured sounds, as well as in the computed flow-induced vessel wall displacement, supports the hypothesis that AVF sounds result from the propagation of flow-induced vascular wall vibrations through the surrounding tissues. This interpretation is in line with previous hemoacoustic modelling studies and is more broadly compatible with Lighthill's acoustic analogy and its extensions by Curle and Ffowcs Williams–Hawkings, which described how turbulent flow and wall interactions generate and radiate sound into the surrounding medium. Our results are also compatible with Howe's vortex-sound theory, according to which coherent vortical structures generate an unsteady pressure field and act as acoustic sources. Our findings can therefore be interpreted within a rigorous paradigm, in which complex flow in the vascular lumen excites wall vibrations that act as sound sources.

From a clinical perspective, the possibility of linking hemodynamic patterns to well-characterised wall vibrational and related vascular remodelling is promising (Soliveri et al., 2026; Soliveri et al., 2024). This study adds the observation that the frequency content of AVF sounds and AVF wall vibrations closely match, suggesting that sound signatures may encode mechanistic information about AVF haemodynamic conditions. By adding advanced computational modelling to clinical auscultation,

our results strengthen recent evidence that shows that sound carries valuable information on haemodynamic complexity and blood flow adequacy in an AVF (Poloni et al., 2024). Specifically, the presence of the strong high-frequency component could be associated with disturbed or transitional flow, whereas more laminar accesses tend to concentrate power in lower-frequency bands (Poloni et al., 2024). This could be considered a fingerprint of remodelling-prone haemodynamic environments: distinct frequency bands could serve as biomarkers of flow conditions, potentially allowing earlier identification of AVF dysfunction. In addition to this, the sound itself has strong potential to detect AVF dysfunction (Ota et al., 2020).

Although promising, current results should be considered as preliminary, given the limited dataset of four AVF patients and the predominantly qualitative nature of the spectral analysis, which is based primarily on visual comparison of the computed spectra. Furthermore, the AVF acoustic recordings were obtained with a specific electronic stethoscope, whose frequency response characteristics may have slightly influenced the spectral representation. Nevertheless, the overlap observed between computational results and clinical measurements suggests that the identified coupling is robust.

Future studies adopting more advanced acoustic propagation models, accounting for tissue heterogeneity and multi-layer

transmission, could further strengthen the link between computed vessel wall vibrations and sounds detected at skin level. Finally, larger and longitudinal cohorts will be essential to confirm these results, establish quantitative correlations between AVF flow dynamics, vessel wall vibrations, and sound features, and assess whether changes in acoustic signatures over time can be used to infer specific haemodynamic patterns and early detection of AVF dysfunction.

CRediT authorship contribution statement

Sofia Poloni: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Luca Soliveri:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Kristian Valen-Sendstad:** Writing – review & editing, Supervision, Software, Conceptualization. **Anna Caroli:** Writing – review & editing, Supervision, Conceptualization. **Andrea Remuzzi:** Writing – review & editing, Supervision. **Michela Bozzetto:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The code used for fluid–structure interaction simulations is available

in VaSP github repository at <https://github.com/KVSlab/VaSP>. Data are available on the Zenodo platform and will be shared upon reasonable request to the authors.

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