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Simulation-aided workflow toward dynamic fluid phantoms for impedance plethysmography

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Abstract: Impedance plethysmography (IPG) is recently gaining traction as a non-invasive sensing technique suitable for wearable devices, such as smartwatches. In this context, dynamic fluid phantoms can provide well-defined test scenarios to enable algorithm design and training. We outline the initial steps of our phantom design process, which relies on a combination of simulation studies and experiments. We conducted measurements in saline solutions and implemented a corresponding simulation of a time-varying pulse wave. Our overarching goal is the integration of an IPG component into a multi-modal dynamic fluid phantom.

I. Introduction

Bioimpedance, the study of the electrical properties of biological tissues, is typically conducted by injecting a constant current and measuring the resulting voltage [1]. Depending on the frequency range and electrode placement, different physiological parameters can be examined. Impedance plethysmography (IPG) focuses on the assessment of fluid volumes, e.g., blood volume changes caused by the local pulse wave in the extremities [2].

Impedance phantoms allow for systematic research on the basic characteristics of impedance measurements. An impedance phantom must match the electrical properties of the physiological structures in the desired test conditions. This can be implemented in a stationary or dynamic way. The former has been long-standing practice in electrical impedance tomography (EIT) phantoms. Test objects, often pieces of vegetables, are placed in cylindrical tanks to model conductivity distributions comparative to trans-thoracic impedance measurements [3].

The replication of time-varying processes in IPG requires actuated phantoms, which can mimic the underlying dynamic processes related to cardiac activity. Respective solutions are rare. *Yu et al.* [4] implemented a gelatine-made human wrist phantom to assess the arterial diameter. It was powered by an injector pump to achieve different (quasi-stationary) pressure levels.

In contrast, our approach aims at IPG measurements in a fluid circulation system. The latter is part of an existing dynamic fluid phantom, which was initially used for photoplethysmographic (PPG) applications [5]. By adding impedance-related subsystems, we aim to incorporate complementary sensing techniques, e.g., for a multi-modal assessment of blood pressure. In this paper, we approach this goal with initial experiments and derived simulations on time-varying operating conditions.

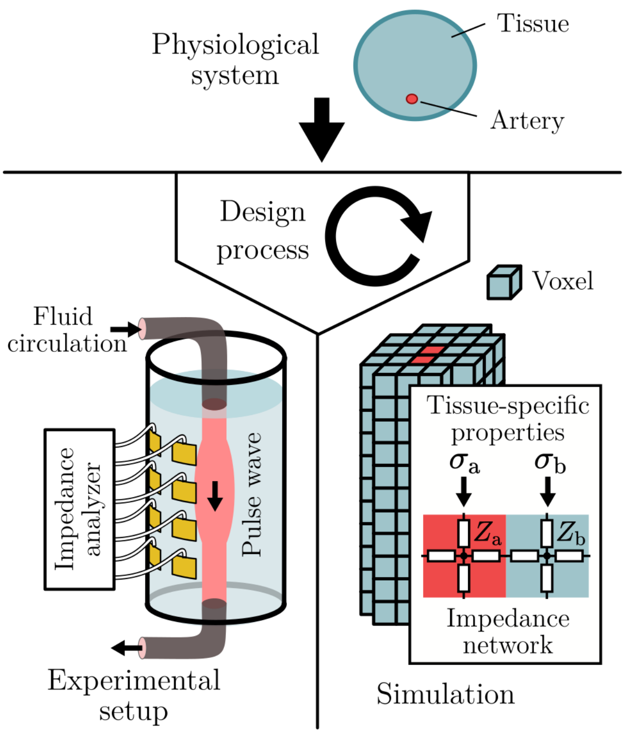

Figure 1: Phantom design workflow using simulation and experimental setup.

II. Material and methods

To implement the dynamic fluid phantom, we chose a two-pronged strategy (see Fig. 1) with a physical experimental setup based on saline solutions of different conductivities aided by a software-implemented simulation approach.

II.I. Experimental setup

We implemented an experimental setup centered around a multi-frequency impedance analyzer (Sciospec Medical Research ISX-3). It includes an acrylic glass cylinder (50 mm inner diameter) equipped with electrode arrays (see Fig. 2). Based on [4], we prepared NaCl solutions of different concentrations with deionized water to model higher-conductivity blood (Solution A: 0.08 M/l, 0.73 S/m) and lower-conductivity tissue (Solution B: 0.017 M/l, 0.16 S/m) within the cylinder.

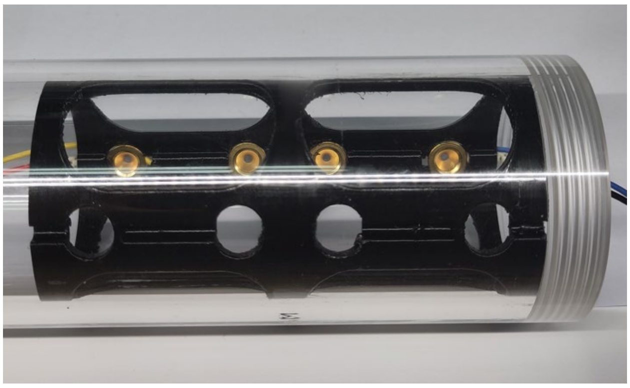

Figure 2: Experimental setup with 4-electrode linear array.

II.II. Simulation

We set up a basic electrical simulation in Python to model the tissue (saline solution) as an impedance network (cf., Fig. 1) [6]. Each voxel is coupled to each adjacent voxel by an impedance. Surface voxels can optionally be connected to electrodes for current input and voltage measurements. With known voxel impedances and input currents, nodal analysis can be applied to obtain a linear equation system, which can be solved by SciPy's conjugate gradient method. This results in the voltages (and impedances) for each voxel and across electrodes. Time-varying processes can be modeled by modifying the tissue parameters and solving again.

III. Results and discussion

As an initial experiment, we investigated the behavior of a minimal setup (cf., Fig. 2) in the frequency range from 1 kHz to 100 kHz. We measured a primarily resistive transfer impedance between the inner electrode pair of 16.1 Ω to 15.9 Ω (Solution A) and 71.8 Ω to 72.6 Ω (Solution B). We repeated the experiment in the simulation environment (voxel size: 1 mm) and obtained corresponding values of 15.6 Ω and 71.4 Ω. These values are in good agreement, which indicates a comparable output value range. However, it does not imply an exact match between the setup and the simplified simulation.

Based on these results, we focused on the fundamental behavior of a traveling pulse wave in the simulation (see Fig. 3). At this stage, we did not consider realistic dimensions for pulse wave length and electrode placement. Inside the cylindric dimensions of the experimental setup, we assumed a narrow channel (artery) of higher conductive material with 3 mm radius. The simulated pulse wave (sphere of 4 mm radius) moved in discrete steps of 5 mm through the cylinder.

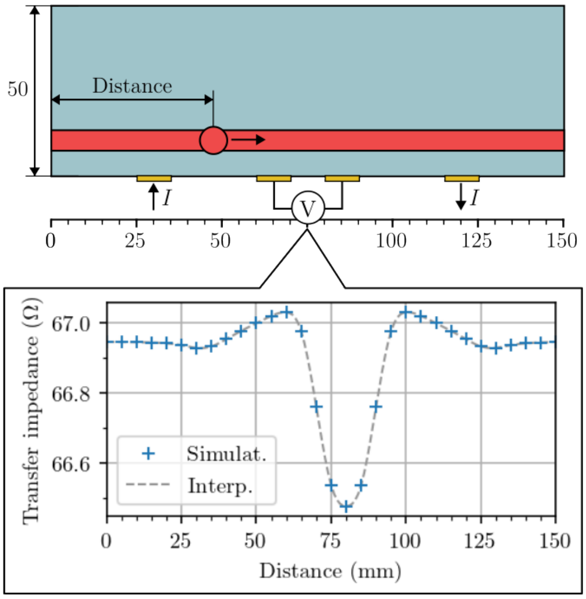

Figure 3: Impedance changes depending on the simulated pulse wave position. Dimensions in mm.

The resulting impedance curve (see Fig. 3) shows a slight increase once the pulse wave passes by the first electrode and a minimum (decrease of 0.5 Ω) at the center of the cylinder. With the overall signal shape and value range, the transfer to a physical experiment seems promising, although experimental results will likely vary. The implementation will also require a physical channel, in which the pulse wave can travel, e.g., a conductive tube or gelatine body.

IV. Conclusions

With our initial experiments and simulations, we implemented the first step toward a dynamic IPG phantom. As next step, the consistency between the simulation-based results and the physical setup should be investigated to facilitate the integration into a multi-modal fluid phantom.

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Author's statement

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