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Validation System for Digital Stethoscopes

Abstract: Stethoscope auscultation is a diagnostic method widely used by medical professionals. With the introduction of digital stethoscopes, auscultation sound analysis has been objectified, which led to an increased interest in the field. Until today, however, no standard to assess the acoustical properties of stethoscopes is available. Some approaches use phantoms mimicking the properties of human soft tissue. In most cases, however, the properties of the phantoms have not been analyzed with respect to environmental variables. In our work, we propose a stethoscope characterization system for the frequency range between 50 Hz and 2.5 kHz with a small financial footprint. We analyzed its frequency behavior over temperature, time and position on the phantom and derived quantitative recommendations for environmental variables. Finally, the frequency response of a commercial digital stethoscope was characterized at different pressure levels. We conclude that the presented system is capable to stably and reproducibly assess the transfer function of digital stethoscopes. We hope that future stethoscope designs will be characterized with respect to their acoustical properties.

Keywords: Digital Stethoscope, Auscultation, Acoustical Properties, Transfer Function, Gel Phantom, Weighting

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1 Introduction

Auscultation using a stethoscope is practiced by a variety of medical professionals. With the introduction of digital stethoscopes which provide better sound quality, can reject ambient noise and are able to record sounds, the analysis of auscultation sounds has been objectified. As a result, the interest in auscultation is rising again. Besides commercially available, traditional digital stethoscopes, some mobile, and even wearable stethoscope concepts are on the horizon [1].

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Figure 1: Half section view through the designed phantom. The exciter is fixated on the bottom of the inner PVC assembly.

For most digital stethoscopes, only the frequency response of the filtering stages are specified. Their acoustical properties, on the other hand, have a large influence on the characteristics as well, and are oftentimes subject to large variations [2]. Until today, there is no established standard to characterize their acoustical frequency response. This problem was already addressed by Ertel et al. as early as 1966 [3]. In the following decades, different approaches have been proposed. Watrous et al. presented a water-filled polymer ball phantom, excited by a shaker and using an accelerometer as a reference [2]. Kraman et al. developed a system termed BATT using a microphone as reference in an air chamber below a viscoelastic surface [4]. Most recently, Weiss et al. compared eighteen stethoscopes using a gel phantom [5]. In a recent study by Nowak et al., four digital stethoscopes have been compared using patient auscultation [6]. Mansy et al. pointed out that the acoustical properties of the phantoms are oftentimes overlooked. To optimize the distribution of energy across the phantom's surface, the authors suggested embedding a plate into the phantom [7]. However, further research is needed regarding the properties of phantoms under different environmental conditions.

In our work, we present a gelatine-based stethoscope characterization system given in Figure 1 with a small financial footprint. The investigated range of 50 Hz to 2.5 kHz covers most frequency components of heart sounds [8] as well as lung and tracheal sounds reaching up to 2.5 kHz [9]. The system's transfer function is characterized over temperature, time and position across the phantom. Finally, a commercially available, digital stethoscope is characterized under different pressure conditions. We hope to encourage acoustical characterization of newly developed digital stethoscopes and to sensitize for the varying acoustical properties of a gel phantom under different conditions in the validation step.

2 Methods

2.1 Design of the Validation System

Without a gold-standard being established for the characterization of digital stethoscopes, a cost-efficient system based on the current state of the art was implemented as given in Figure 1. A PVC flange with an inner diameter of 16 cm and an overall height of 9 cm was used as housing. As phantom material, gelatine was employed, which was shown to well approximate soft tissue [7]. We used a concentration of 20%. Into the gel, a 7 cm high, lathe-turned PVC assembly with 11.5 cm diameter at the top and 8 cm diameter at the bottom was embedded. The PVC assembly carries a 25 W, 8 Ω structure-borne sound converter (Visaton EX 60 s) with a contact area of 5.8 cm x 5.8 cm. This sound converter is used as an inexpensive solution to excite the phantom above 50 Hz. In order to obtain a reference of the generated surface movement, a highly linear, wideband accelerometer (ADXL203CE) was employed, which covers the frequency range of up to 2.5 kHz. The resulting overall frequency range of 50 Hz to 2.5 kHz covers the full relevant spectrum. Please note that throughout this work we analyse solely the magnitude of the complex transfer functions.

The transfer function of the system $H_p(f)$, including the phantom and the sound converter, is derived from the exciter input $V_{exc}(f)$ and the accelerometer output $V_{acc}(f)$ as

$$H_p(f) = 20 * \log_{10} \left(\frac{V_{acc}(f)}{V_{exc}(f)} \right). \quad (1)$$

The ratio between the exciter input and the accelerometer output has the unit $\frac{ms^{-2}}{V}$ and therefore reflects the surface acceleration of the phantom relative to the exciter input voltage. The system's transfer function is expected to be non-constant over the frequency range of interest and to contain resonances at different frequencies. In order to optimize the operation point of the system, given its limited dynamic range, a spectral equalization step similar to the approach presented by Mansy et al. was employed [7]. The phantom transfer function was first characterized using an excitation signal with constant energy over the frequency spectrum. The resulting transfer function was then used to calculate an excitatory signal which counteracts the deviations from the optimal, constant transfer function. The resulting signal was then compressed nonlinearly to stay within the rated output of the sound converter and to guarantee a minimum surface acceleration. We were able to reduce the non-uniformity from 23 dB to below 6 dB. The spectral equalization is performed prior to every measurement.

2.2 Validation System Characterization

Three tests have been performed to characterize the phantom's properties. Firstly, the position dependency of the phantom's transfer function was analysed in 1 cm steps across the diameter of the phantom. Secondly, variations of the transfer function over time have been analysed for 48 hours starting at 16 hours after the cast, at the centre and at a 3 cm offset from the centre. The phantom was stored at 26 °C. Finally, the temperature dependency of the transfer function was addressed. For that purpose, the phantom was cooled down to 9 °C and measurements have been carried out until the phantom reached 22 °C. For all presented data at least two consecutive measurements have been performed and averaged. In addition, every analysis was carried out using two different phantom casts at different days in order to assure reproducibility.

2.3 Digital Stethoscope Characterization

Using the presented system, we characterized a commercial, digital stethoscope at different pressure levels. The stethoscope is configurable in five frequency response modes, four of which aim to approximate different bell and diaphragm responses. The fifth mode, termed “wideband mode” has a frequency range of 20 Hz to 2 kHz and was used for the characterization. The specified frequency response, however, refers only to that of the digital filtering, not to the acoustical response. The acoustical properties of stethoscopes were expected to vary with the applied pressure. Therefore precision weights up to 500 g were used to load the stethoscope. Pressing the stethoscope into the phantom, however, does lead to disturbances in the spatial symmetry of the phantoms transfer function. This results in a distorted frequency responses of the stethoscope which manifest mostly as implausible peaks. Therefore, the accelerometer is placed at a position which results in a system transfer function closest to the unloaded case. The characterization is then carried out using that configuration over all loads.

The transfer function of the digital stethoscope $H_s^w(f)$ at different weights w is derived from the accelerometer output $V_{acc}^w(f)$ and the output of the stethoscope $V_s^w(f)$ as

$$H_s^w(f) = 20 * \log_{10} \left(\frac{V_s^w(f)}{V_{acc}^w(f)} \right). \quad (2)$$

The ratio between the stethoscope output and the accelerometer output has the unit $\frac{V}{ms^{-2}}$ and therefore reflects the stethoscope output amplitude relative to the phantom surface acceleration.

3 Results

3.1 System Characterization

The position dependency of the system's transfer function across the diameter of the phantom is given in Figure 3. With small exceptions, an overall symmetry around the centre of the phantom was found. The system showed a strong resonance for frequencies below 100 Hz at all positions. In the range between -4 cm and 4 cm off center, the frequency response was uniform in the limits of ± 5 dB above 100 Hz with a single pronounced dip at about 700 Hz present in all casts.

Figure 3: System transfer function over distance from center.

The system's frequency response over time at 3 cm off centre is given in Figure 2. Frequency components above 300 Hz are mostly unaffected by the drying process. Below 300 Hz, a shift in the maximum of the frequency response towards higher frequencies becomes visible. Roughly 45 hours after the phantom is cast, the transfer function is more stable

Figure 2: System transfer function over time after phantom cast.

for about 10 hours after which the trend slowly continues. Without a conserving agent and when stored at 26 °C, the phantom becomes unusable 65 hours after the cast due to the development of mould.

The temperature dependency of the system's transfer function is given in Figure 4. Frequencies above 500 Hz are largely unaffected by the temperature of the phantom. At temperatures below 12 °C, the transfer function remains largely constant with pronounced non-uniformities between 100 Hz and 500 Hz. Above 12 °C, peaks and valleys in the transfer function shift towards lower frequencies, diminish by 4 dB and the higher frequency ranges are flattened. With increasing temperature, the rate of change increases.

Figure 4: System transfer function over phantom temperature.

3.2 Digital Stethoscope Characterization

The weight-dependent frequency responses of the digital stethoscope under test are given in Figure 5. With increased weighting of the stethoscope, frequencies between 100 Hz and 250 Hz were amplified up to 20 dB compared to the unloaded case. Frequencies below 100 Hz were less affected and amplified below 10 dB. The frequency range between 70 Hz and 80 Hz showed a prominent dip over all loads. Frequencies between 250 Hz and 1 kHz are only slightly amplified with increased pressure and stayed below 5 dB additional gain under all weighting conditions. The transfer functions fell quickly with about 50 dB per decade in that range. Above 1 kHz, a -10 dB drop is consistently present in all cases, marking the upper frequency limits of the digital stethoscope under test. The overall frequency response had its maximum around 200 Hz in all weighting scenarios. In the range between 50 Hz and 1 kHz, the stethoscopes transfer function ranged from -20 dB to +20 dB. No additional sharp resonances or dips have been identified.

4 Discussion and Conclusion

The transfer function of the presented system was symmetric across the diameter of the phantom. While the positions -3 cm and 3 cm off centre have been identified for placing the device under test and the reference respectively, adjustments may be needed in the loaded case. The system's transfer function is most stable after 45 hours, however, changes are sufficiently slow for typical measurements after 24 hours. Including a conserving agent into the phantom is recommended if usage for more than 60 hours is planned. Above 12 °C, the frequency response changes rapidly with the temperature. Higher temperatures tend to flatten the transfer function of the system. For temperatures beyond 30 °C, the phantom became physically unstable. A temperature controlled environment between 20 °C and 26 °C is recommended. It is worth noting that each phantom cast had a slightly different transfer function, most evident from the location of the first sharp dip in Figure 2 and Figure 4. A reference system to characterize the surface vibration while performing the measurement is therefore imperative.

When characterizing the stethoscope, low-frequency amplification with increased pressure was found as expected. Due to the changes in the phantom's acoustical properties over temperature and time, spectral equalization is recommended before every measurement. However, the stethoscope transfer functions have been stable and reproducible over different phantom casts, temperatures, positions on the phantom and times after the cast when following the described procedure, underlining the importance of the reference accelerometer. Please note that the frequency responses shown in Figure 5 are that of the specific device and do not apply for other stethoscopes.

Two major limitations of the system described are the dynamic range and the altered spatial distribution of energy when weighting the phantom. Their impact on the results have been alleviated by the methods described, however, further optimizing these parameters may be beneficial.

We conclude that the presented system is capable of reproducibly assessing a stethoscope transfer function despite its small financial footprint. The derived recommendations for environmental variables should allow for stable measurement conditions and the given procedure largely compensates for system imperfections. We hope future stethoscopes will be characterized with regard to their acoustical properties to allow for a quantitative comparison between systems.

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Figure 5: Loaded frequency responses of the digital stethoscope.

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