Arterial pulse waves measured with EMFi and PPG sensors and comparison of the pulse waveform spectral and decomposition analysis in healthy subjects

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Abstract

The purpose of this study is to show the time domain and frequency domain analysis of signals recorded with Electromechanical Film (EMFi) and Photoplethysmographic (PPG) sensors in arterial elasticity estimation via pulse wave decomposition and spectral components obtained from left forefinger, wrist, and second toe arteries. ECG and pulse waves from the subjects were recorded from 7 persons (30-60 y) in supine position. Decomposition of the pulse waves produces five components: percussion, tidal, dicrotic, repercussion, and retidal waves. Pulse wave decomposition parameters between EMFi and PPG are compared to detect variables for information on person's arterial elasticity. Results show that elasticity information in the form of pulse wave decomposition from PPG and EMFi waves is obtainable and shows clear shortening between percussion wave and tidal wave peak time in PPG waveforms with age. The spectral information obtained with frequency domain analysis could also be valuable in assessment of the arterial elasticity. In addition, both PPG and EMFi measurements are absolutely non-invasive and safe. In PPG measurement, the sensors are on the opposite sides of the finger tip, however, EMFi measurement needs the good skilled operator attaching the sensor on the patient's wrist by touching gently to obtain accurate waveforms.

Keywords: arterial elasticity measurement, electromechanical film (EMFi), photoplethysmography (PPG), pulse wave decomposition

Introduction

Arterial pulse wave is defined as a heart-beat driven wave of blood that propagates via each artery into vein through capillaries. Various kind of medical information can be obtained by the detection of pulse wave and its detailed analysis. This information is not obtainable from the blood pressure or electrocardiographic measurements. It could be possible to make early diagnosis on the basis of the pulse wave analysis. Especially atherosclerosis is the main cause of circulatory diseases. Its quantitative assessment is essential for making an early diagnosis of such diseases. In addition, persons with other cardiovascular diseases (CVD) may have decreased arterial elasticity compared with those free of CVDs. Change of arterial elasticity is one of the early markers of accelerated arterial aging and can correlate with many coronary risk factors. Especially arterial elasticity reflects the arterial and aortic expanding during left ventricular contraction. Arterial elasticity can be measured indirectly provided the measurement method is relevant and accurate enough. In this study, biophysical function and structure of the arteries have been measured by photoplethysmographic (PPG) and electromechanical film (EMFi) sensors. For the measurement data, we applied pulse wave decomposition (PWD), which reflects clearly the elasticity of the aorta and its peripheral arteries. The combined PPG & EMFi measurements can establish aortic and arterial elasticity based on PWD of the both signals during a heart cycle. We do not necessarily need distance measurement required for pulse wave velocity estimation, which can be rather inaccurate in the case of the arterial tree [1]. The EMFi and PPG technologies require a few electromechanical or opto-electronic components: a EMFi film sensor connected to an amplifier, and a light source to illuminate the tissue (e.g. finger), and a photodetector to measure the small variations in light absorbance amplified also by a transimpedance amplifier. The obtained pulse wave is the peripheral pulse that can be decomposed into five logarithmic normal components. Despite its simplicity, the origins of the different components of the PPG or EMFi signal are not fully understood [2]. We believe that these parallel pulse waves can provide valuable information about the circulatory system with patient-friendly and safe means.

In the elderly and in the stiffened arteries, the forward and reflected pulse waves travel faster, i.e., pulse wave velocity (PWV) is higher than in a young person's arteries which are elastic. The arterial waves reflected from the periphery of the arterial tree, return earlier merging with the systolic part of the incident wave causing augmentation of the workload of the heart. Favorable softness between coupling of the left ventricle and the arterial tree is thus progressively lost. This loss can be greatest in the aorta, and least in the upper limbs. The wave reflection of the pulse wave due to increase in PWV also increases with age, but can be largely prevented by physical activity and proper diet. The amplitude spectrum of the ECG, EMFi, and PPG are changing by so-called integral pulse frequency modulation (IPFM) [3]. This modulation is caused by the autonomic control mechanisms of cardiac functions which are involved in short-term fluctuations in the time interval between the consecutive heart cycles. The IPFM reflects cardiac function which is also detected in the periphery of the arterial tree. Healthy modulation in coupling of the left ventricle and the arterial tree is, however, progressively lost.

In our study we measure EMFi, two PPGs, and ECG signals, and we apply Fast Fourier Transform on the signals in addition to logarithmic normal function decomposition of the EMFi and PPG pulse waveforms.

Methods

In this study, the PPG sensors are based on LEDs and photodetector, EMFi sensor is based on a plastic EMFi film, and ECG sensors are standard electrodes. Changes in light absorption, in the pressure, or in electrical potentials are acting on each sensor generating a measurable voltage. The EMFi sensor acts as a sensitive pressure sensor and the PPG sensor as a sensitive absorbance sensor. Signals from ECG, PPG, and EMFi sensors were recorded with the

PC from 7 healthy persons (30-60 y) using a data acquisition card with the sampling frequency of 500 Hz. ECG signal was used as reference in detecting features from the PPG and EMFi related signals. Pulse wave series from EMFi, PPG finger and toe were processed by Origin software as follows. Firstly, the alternating baseline on each signal bottom (minimum) was searched and then subtracted. Secondly, the peak of each signal (maximum) was searched, and the average of the peak values was calculated. The signal was divided by the average to obtain the baseline removed and normalized waveforms which has amplitude from the zero to round about one. Processing continues a pulse by a pulse in the PWD.

Results

An example pulse wave from each sensor is shown in Figure 1 on which analysis in time domain and FFT in frequency domain was performed. Each pulse wave component from EMFi, PPG finger, and toe were processed by the software. Decomposed pulse waves from the left wrist (EMFi), and from the left forefinger and the left second toe (PPG) are decomposed in time domain and transformed in frequency domain. In Figure 1 it is shown EMFi (solid), PPG finger (dash dot), PPG toe (dashed) pulse waves, and electrocardiogram (ECG) (dot). They have the start time as zero and then decomposed with their residual and confidence intervals, respectively, in the Figure 2.

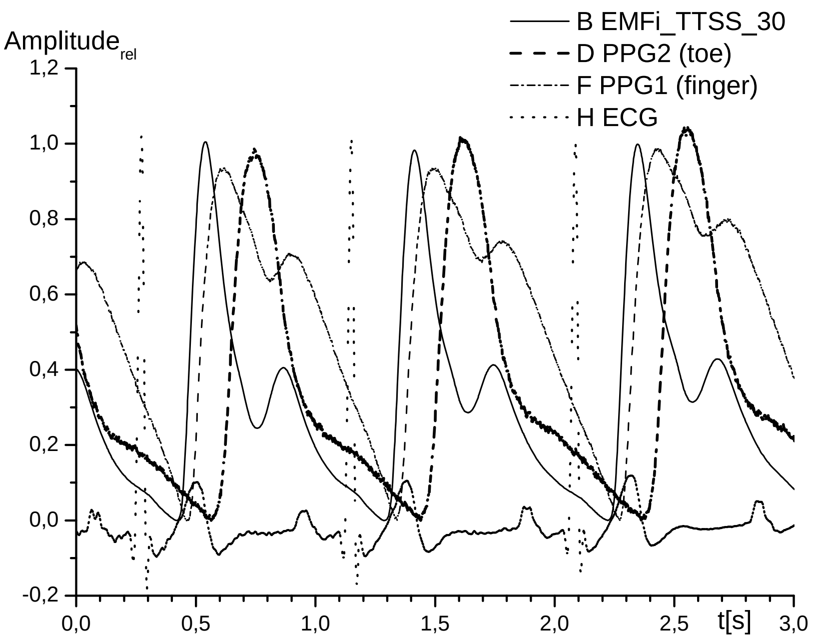

Figure 1. The baseline removed normalized pulse waves: EMFi (left wrist, solid), PPG1 (left forefinger, dash dot), PPG2 (left second toe, dashed), and ECG (dot) (Male 30).

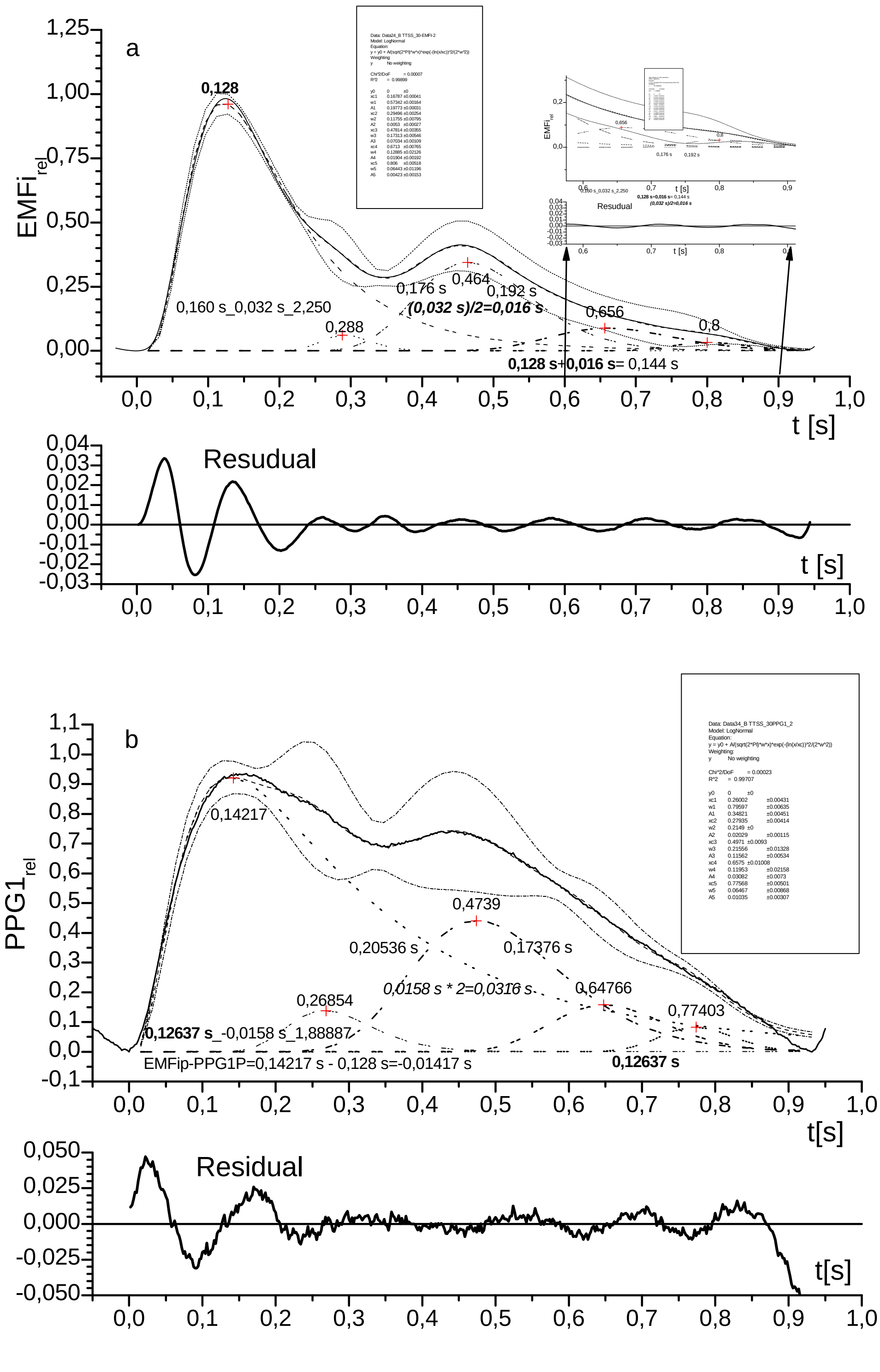

Figure 2a) A single EMFi pulse wave (solid, measured) which is here decomposed into components: percussion (dash), tidal (dot), dicrotic (dash dot), repercussion (short dash), and retidal wave (short dot). (Insert the two last wave components). The confidence interval (99%) is marketed short dot dot. The residual curve is shown in the lower panel. b) A single PPG1 (finger) pulse wave decomposed, respectively. (Male 30).

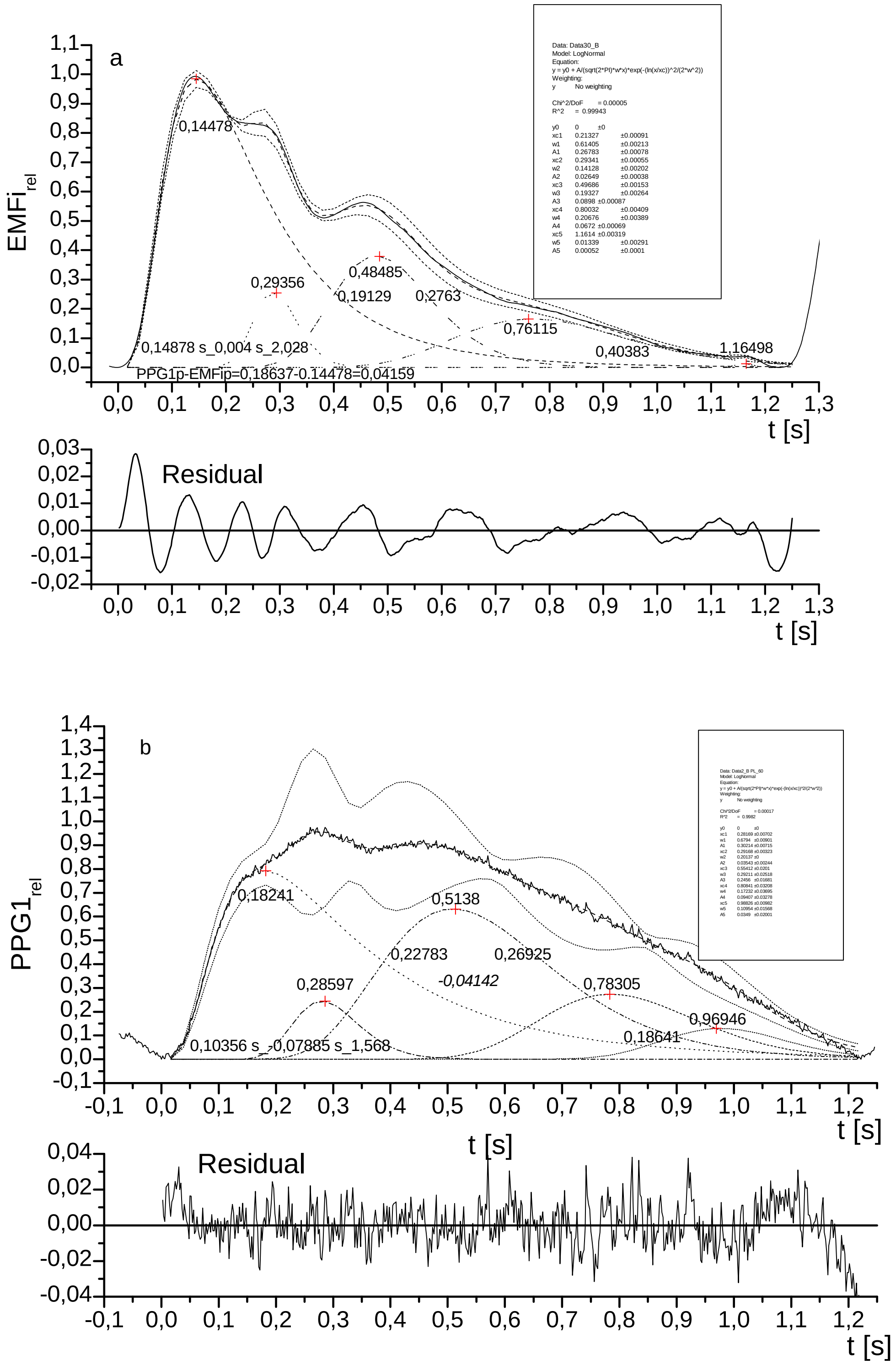

Figure 3a) A EMFi pulse wave (solid, measured) which is decomposed into components: percussion (dash), tidal (dot), dicrotic (dash dot), repercussion (short dash), and retidal wave (short dot). The confidence interval (99%) is marketed short dot dot. The residual curve in the lower panel. b) A single PPG1 (finger) pulse wave decomposed, respectively. (Male 60).

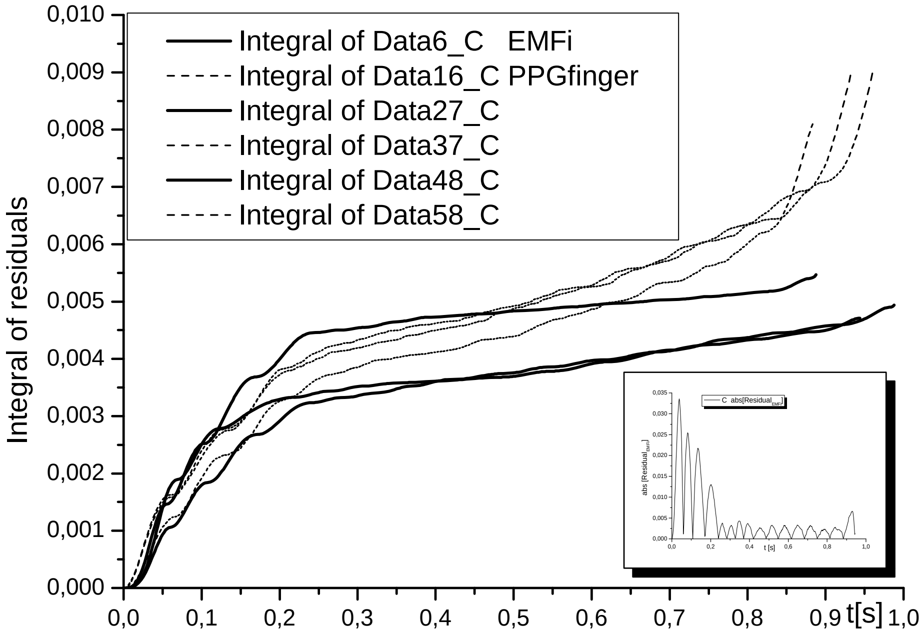

Figure 4. Integral of residuals (EMFi solid) and PPG1 (finger, dash). Insert: Absolute value of residual of EMFi wave-form, (Male 30).

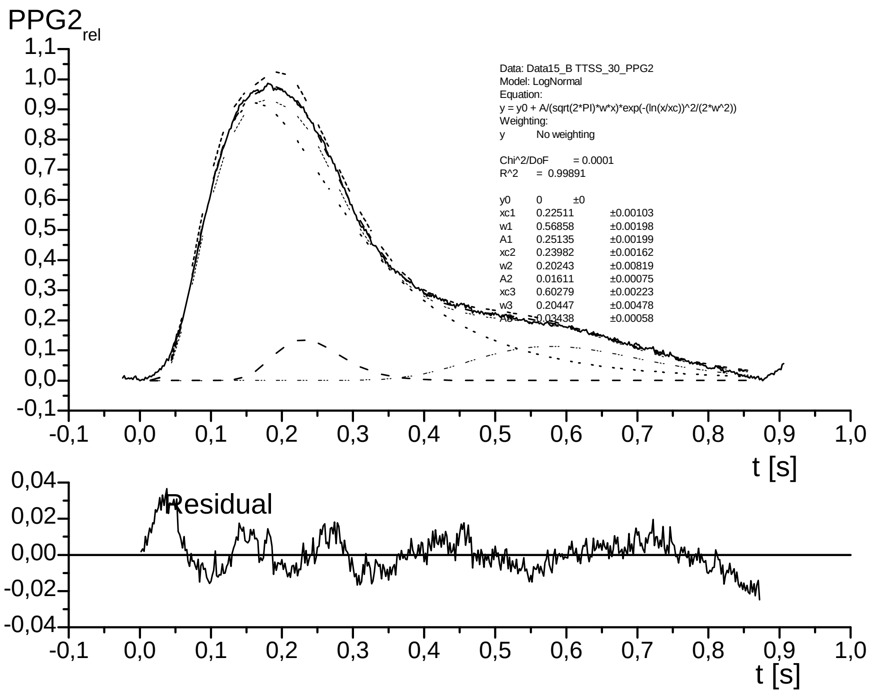

Figure 5. The whole single PPG2 pulse wave (black, measured) which is here decomposed into components respectively as in Figure 2, but here only three components are found. (Male 30, Fig. 1).

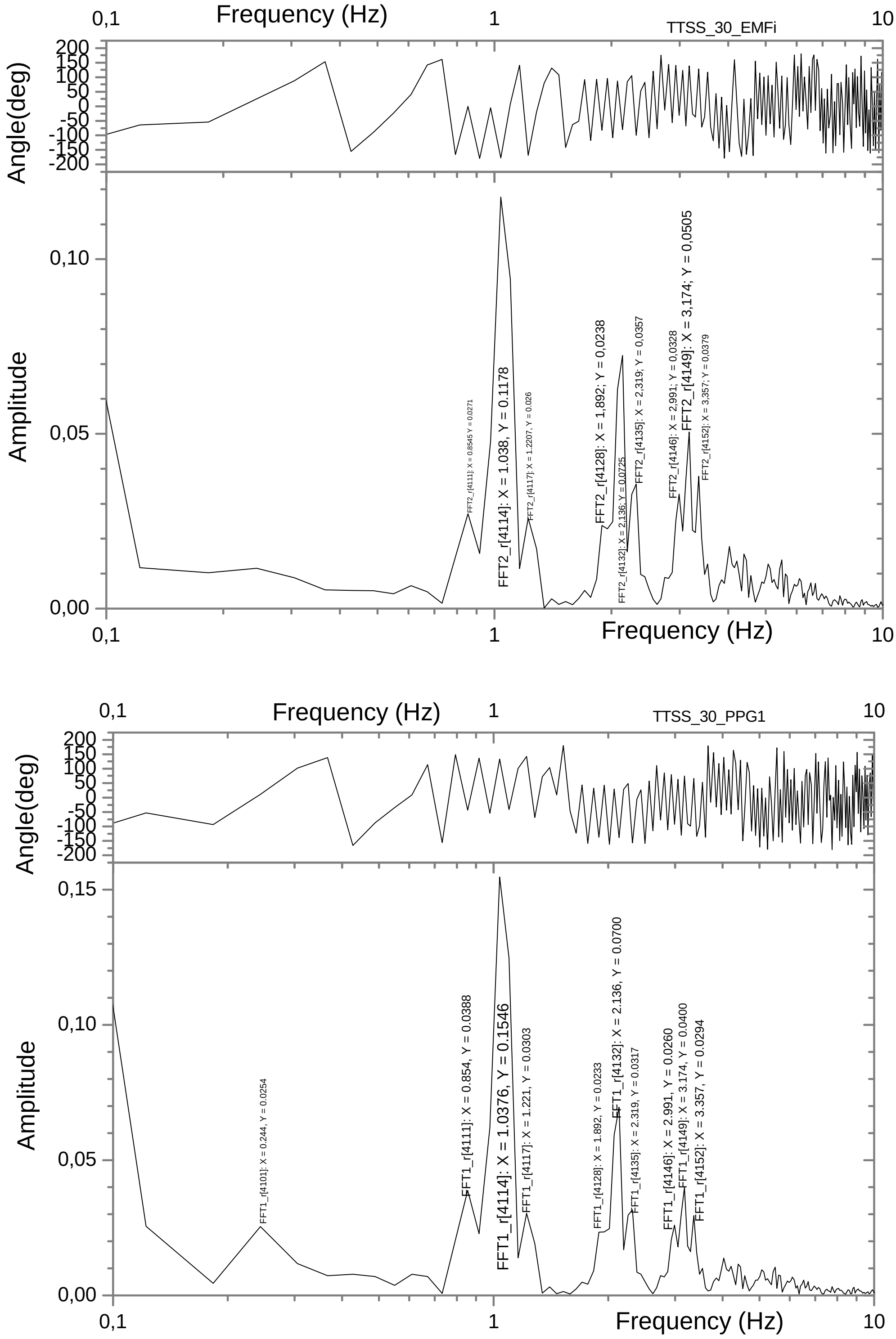

Figure 6. The pulse wave of EMFi's amplitude spectrum (up), and of PPG1's amplitude spectrum (down) with the IPFM parameter values for the three first components for 20 s record. In the PPG1's amplitude spectrum contains the breath rate frequency value (Male 30).

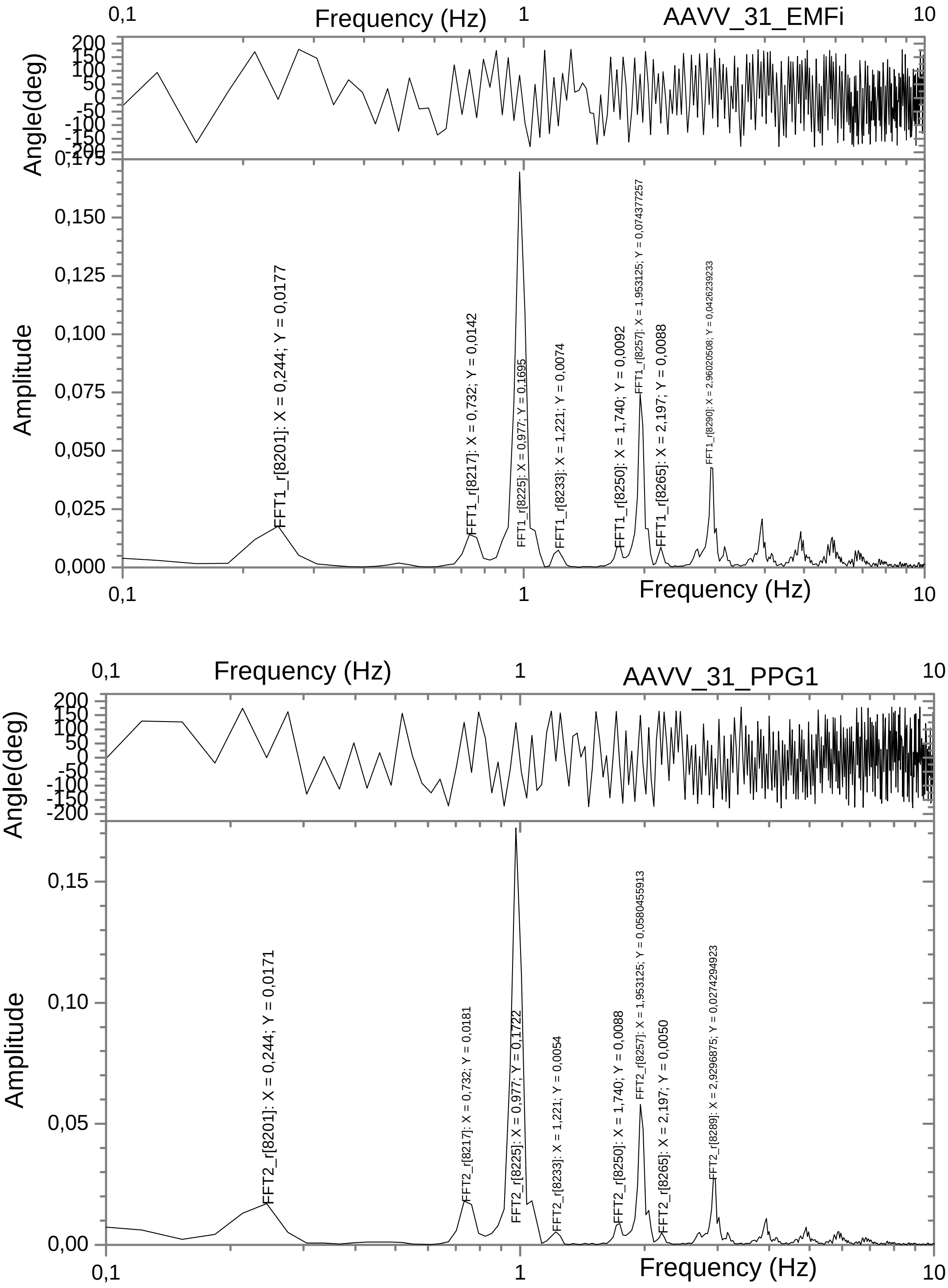

Figure 7. The EMFi pulse wave signal's amplitude spectrum (up), and of PPG1's amplitude spectrum (down) with the IPFM parameter values for the three first components. In the PPG1's and EMFi's amplitude spectrum contain also the breath rate frequency value for 20 s signal record as a sample length (Male 31).

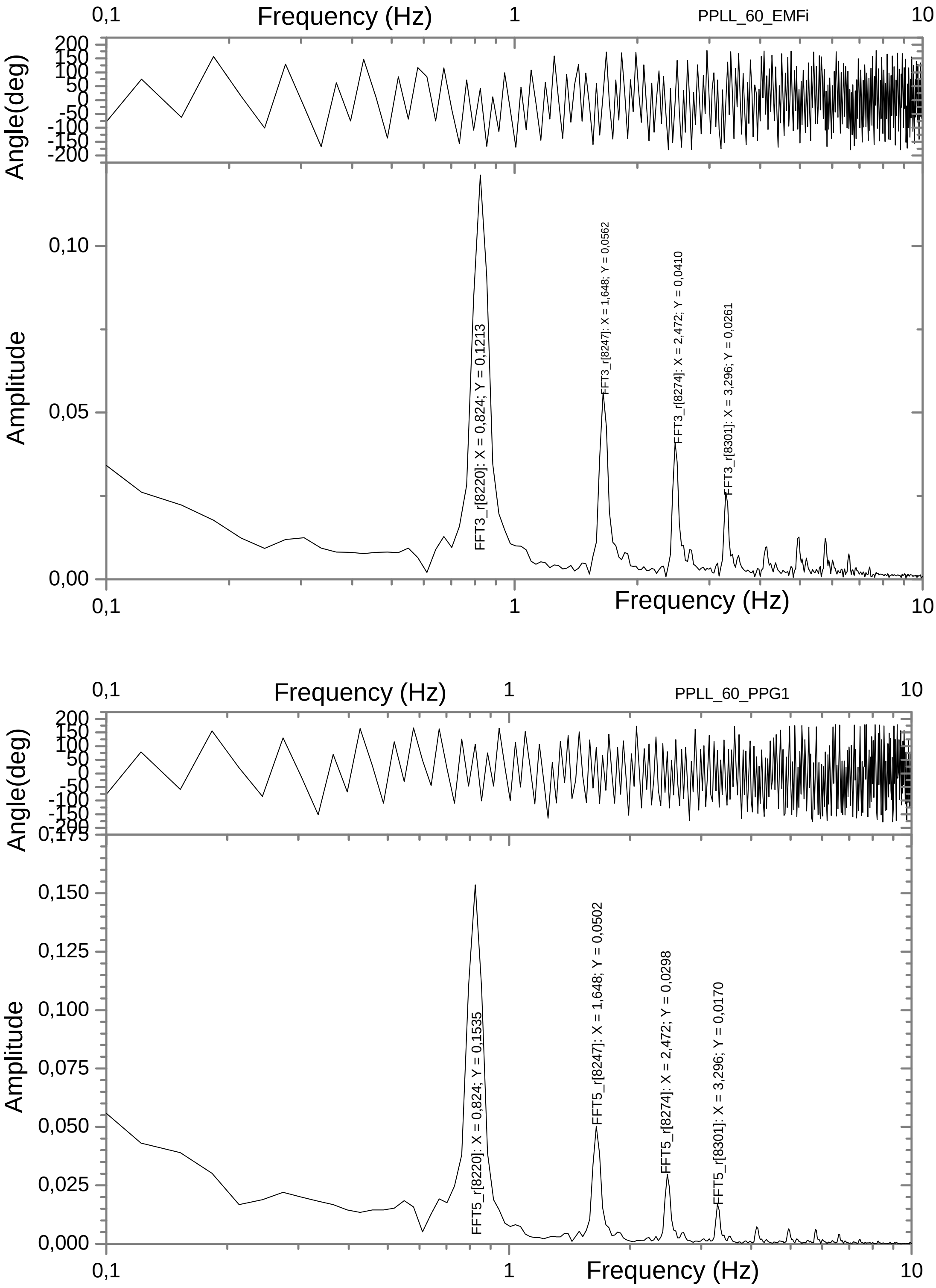

Figure 8. The EMFi pulse wave signal's amplitude spectrum (up), and of PPG1's amplitude spectrum (down). In the PPG1's and EMFi's amplitude spectrum contain also the breath rate frequency value (Male 60).

The comparison of the PPG1 pulse waves shows that the tidal wave comes closer to the percussion wave peak value when person's age increases becoming shorter than the percussion wave defined from the start to the wave maximum (Fig. 2b and 3b). The integrals of residual errors for each sensor and in different measurement show good relation. At the first, the integral of each residual overlaps and then EMFi and PPG based residuals differ after the systolic phase (Figure 4). In Figure 5 it is shown a typical toe PPG pulse wave which contains at least three components according to the decomposition. The comparison of both the EMFi's and PPG1's amplitude spectra shows that the modulation frequency disappears or comes close to the carrier frequency as the person's age increases (Fig. 6, 7, and 8). This study shows also that both the EMFi and PPG pulse waveforms can be decomposed to their component waves, namely, percussion wave, tidal wave, dicrotic wave, repercussion, and retidal waves. Also in frequency domain the amplitude spectra of the respective pulse waves contain at least five or six frequency components.

Discussion

Clinical research is necessary to quantify the ageing effects in relation to the obtained variables and also to explore pulse waveform changes with subject age. However, based on these optical and mechanical measurement methods it was shown the changes in the pulse waveform. Measurement reliability and repeatability is very good provided the EMFi measurements are done by a skilled operator. Pulse waveform analysis of both the PPG and EMFi offers an alternative means of non-invasive cardiovascular monitoring, but further both software and hardware development is required to enable user-friendly clinical and preclinical measurement and analysis system. In PPG, the sensors are on the opposite sides of the finger tip, however, EMFi needs the good skilled operator (A.V.) attaching the sensor on the patient's wrist by touching gently to obtain waveforms. The elasticity is obtained quantitatively from both EMFi and PPG pulse signals both in time and frequency domain because of the components time interval changes or the spectral changes clearly inspected. However, from time domain, decomposition into logarithmic normal function, differs from that obtained from frequency domain because the latter contains many pulse waves which are IPFM modulated and they frequency components overlap. This information from the pulse wave propagation analysis can't be received. In studies, EMFi and PPG theory should be described when analyzing arterial pulse wave signals because they contain effects of respiration, autonomous nervous activity, gastric mobility, and also arterial properties, i.e., arterial diseases.

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