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Ph.D. THESIS SUMMARY

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CONTRIBUȚII LA ACHIZIȚIA ȘI ANALIZA ELECTRONICĂ A SEMNALELOR BIOLOGICE

CONTRIBUTIONS TO ELECTRONIC ACQUISITION AND ANALYSIS OF BIOLOGICAL SIGNALS

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Content

Chapter 1

Introduction

1.1 Presentation of the field of the doctoral thesis

The digitization and processing of data represent a significant advancement in information technology over the past century. This development has had a profound impact on various sectors of society and industry, leading to major transformations in the methods and workflows involving human activity. Among these, some of the most relevant areas include: improving efficiency and productivity in research and development, accelerating innovative technologies, and enhancing decision-making processes.

The analysis of biomedical signals acquired through electronic methods is an expanding technological trend driven by the need to improve health monitoring in both clinical and personal settings. This new direction is particularly promoted by the popularity of smart wearable devices such as watches, bracelets, patches, and rings. Consequently, advances in sensor technology have enabled the capture and recording of complex signals, such as heart rate, brain activity, or blood glucose levels, with high precision and accuracy. The synergy between information processing power and the capability of sensors to measure various stimuli has transformed the way health is monitored. Both healthcare professionals and regular users now have increased accessibility to real-time evaluation of vital parameters and detection of potential anomalies. This integration of technology and information processing brings significant benefits in the prevention and management of medical conditions, thereby improving quality of life and reducing the costs associated with treatments and medical care.

A relevant field is the non-invasive monitoring of the cardiovascular system using smart wearable devices. This trend became significant starting in 2013, when the first smartwatch integrated heart rate monitoring using optoelectronic technologies, with photoplethysmography being the most representative. Thus, health monitoring through smart devices has become a powerful tool for understanding and managing cardiovascular conditions. This contributes to improving diagnosis, planning interventions, and managing post-operative care in a more precise and personalized manner.

By combining electronics and information technology with physiology, new health evaluation markers are created compared to the traditional ones. This synergy brings forth a new paradigm in health monitoring and management, intelligently integrating physiological data with digital technology. Instead of isolated evaluations and sporadic measurements, users now benefit from a continuous approach to their health, based on objective data and real-time recordings. With the advantage of wearable technologies, characterized exclusively by biomedical sensors, a user can benefit not only from improved monitoring but also from personalized care. Consequently, this convergence between digital technology and physiology opens up new horizons in health management and promotes a preventive and personalized approach to medical care."

1.2 Scope of the doctoral thesis

The primary objective of this thesis is to make significant contributions to the field of processing and interpreting biomedical signals acquired through electronic systems. This area is particularly relevant and timely in the current context because, despite remarkable progress, a high level of maturity has not yet been achieved. Thus, there is a continuous need for research and the development of new methods and algorithms that allow for a more precise and efficient interpretation of biomedical signals. However, to make meaningful contributions in a pragmatic and feasible manner, certain critical steps are necessary.

A necessary objective is to understand the physiological mechanisms captured by electronic systems. This step involves a detailed analysis of the biological processes involved in generating essential biomedical signals, such as blood pressure and arterial pulse. The thesis investigates how these physiological processes can be quantified and measured using electronic technologies, such as piezoelectric sensors for measuring blood pressure or optoelectronic methods for recording pulse oximetry. Since the latter method is particularly relevant due to the popularity of smart wearable devices, this doctoral thesis will define an associated model. This model will provide a clear understanding of the origin of the optical signal and its interaction with the cardiovascular system.

Using the knowledge gained, the doctoral thesis will explore areas of non-invasive monitoring with electronic systems in terms of feasibility. Understanding the technical limitations, especially those associated with optoelectronic methods, will define new approaches for processing and interpreting the acquired signals. The most important activity is the correct detection of cardiovascular events and the segmentation of information. Various measurement conditions, particularly those characterized by the nonlinear and quasi-stationary nature of biological systems, will be evaluated in interaction with the extracted information. Therefore, this step will lead to the definition of new signal algorithms for the correct interpretation of the measured data.

Leveraging the results of these investigations will converge in defining medical applications with significant potential for managing cardiovascular conditions. These applications will explore two dimensions of managing potential cardiovascular issues: active monitoring and hemodynamic event detection. In the first dimension, the focus is on characterizing cardiac performance in a temporal context, involving continuous monitoring of periodically modulated parameters that define cardiovascular performance. Active monitoring in this dimension provides the possibility to promptly identify and intervene in the case of anomalies or fluctuations that could indicate health problems. In the second dimension, the focus is on detecting morphological variations of the signal to identify and interpret hemodynamic changes that may indicate a deterioration in cardiovascular performance. By identifying and assessing these morphological variations, more precise and sensitive monitoring of hemodynamic status can be provided, thus enabling preventive interventions and more efficient management of conditions. By exploring these two dimensions, emerging medical applications have the potential to maximize the efficiency of the diagnostic process, treatment planning, and management of health status evolution.

1.3 Content of the doctoral thesis

This thesis is organized to consistently present the methods for processing and interpreting biomedical electrical signals associated with the cardiovascular system. After the introductory chapter, the thesis is structured as follows:

Chapter 2 presents the main characteristics of electrical signals specific to the cardiovascular system. It will define the physical elements involved in the modulation of acquired waveforms, such as blood flow, arterial pressure, and arterial impedance. Additionally, various cardiovascular scenarios that influence these parameters, as well as the morphology of digital measurement signals, will be presented.

In Chapter 3, using an exhaustive analysis of digital databases, hemodynamic mechanisms leading to different morphological behaviors of the recorded signals will be proposed. The most representative signal waveform components found in the literature are the reflected wave and the dicrotic wave. These proposed models will be investigated under various scenarios to provide an efficient decision-making factor for patient management. The findings from the analysis and interpretation of the arterial pressure electrical signal will serve as the initial foundation for investigations into photoplethysmography techniques.

Chapter 4 will begin by investigating the origin of the optoelectronic signal, PPG, as it represents a popular technology in smart wearable devices. Based on a practical experiment, an associated model will be defined to understand the relationship between cardiovascular behavior and the recorded signal morphology. Using digital databases, the feasibility of this technique for characterizing hemodynamic states will be analyzed. The sources of noise that affect the waveform interpretation process and the technical limitations that intrinsically arise from human biological behavior will also be presented.

With an improved level of maturity in interpreting the aforementioned digital signals, Chapter 5 will present medical applications. These applications will focus on processing the optoelectronic PPG signal for advanced cardiovascular or hemodynamic characterization. Two independent dimensions of the waveform will be analyzed: the temporal dimension and the morphological dimension. In the first case, the proposed application will determine cardiac period performance, while in the second, it will detect the presence of anomalies, which translate into cardiovascular dysfunctions.

The final chapter will present the conclusions of the individual investigations based on the obtained results, the original contributions, the list of works, and future directions in the field of interpreting biomedical signals acquired through digital methods.

Chapter 2

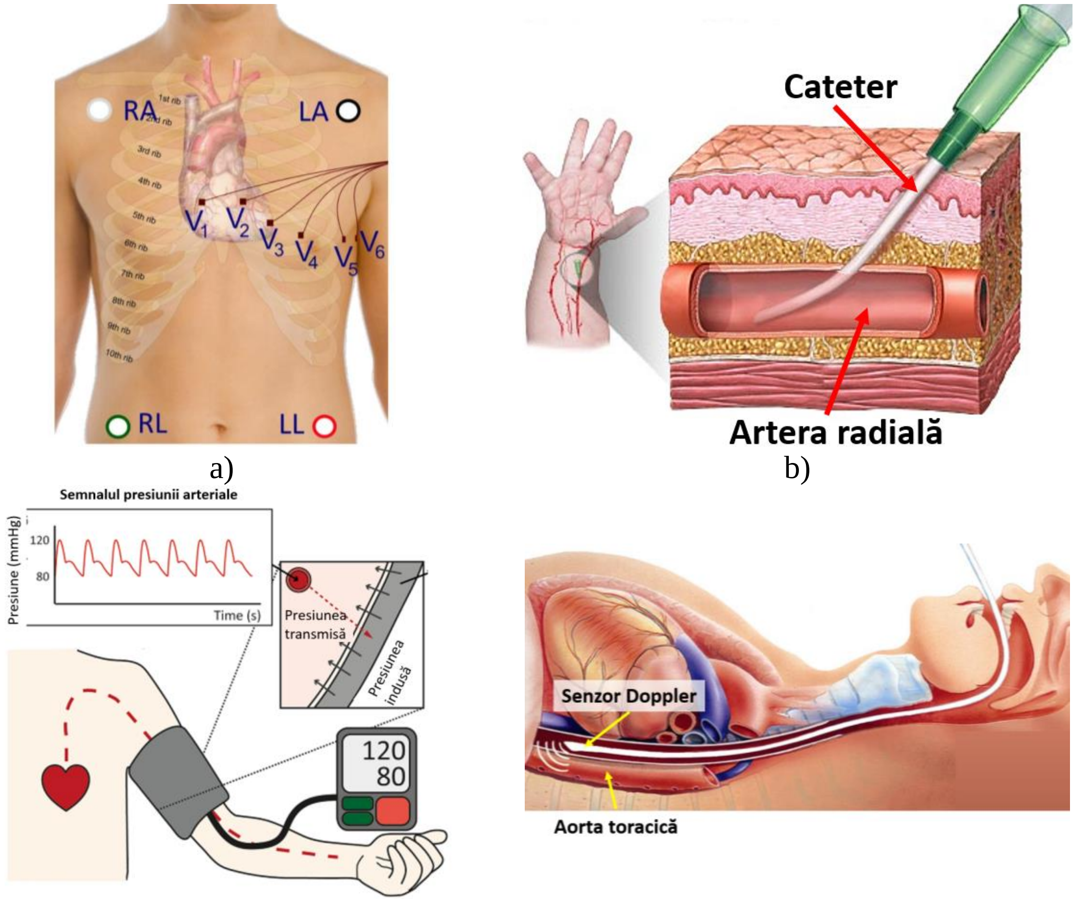
Characterization of cardiovascular activity using electrical signals

Health monitoring using technological devices has become increasingly important due to several factors, including technological advancements, increased awareness of personal health, and the need to manage chronic diseases. The key aspects regarding the usefulness of these devices include prevention, detection, management, and treatment of chronic conditions [1,2,3].

In this context, monitoring the cardiovascular system using devices and medical equipment is an essential activity. From a medical perspective, its performance is primarily characterized by the individual functioning of the heart and blood vessels [11,12]. Currently, there is a wide range of medical devices that digitally process acquired cardiovascular information, such as: computed tomography (CT) [13], tissue Doppler imaging (TDI) [14], vascular Doppler ultrasound [15], electrocardiogram (ECG) [16], and invasive blood pressure measurement [17]. In the context of wearable devices, which are a precursor to smart devices like watches and bracelets, the most popular evaluation methods that result in an interpretable temporal signal are:

- Electrocardiogram (ECG) [18], Figure 2.1 a) – a measurement technique that records the bioelectrical activity of the heart using capacitive sensors. The electric field generated by the signals of cardiac contractions is obtained by placing a reference electrode and at least two acquisition electrodes.

- Invasive Arterial Pressure (ART) [19], Figure 2.1 b) – a measurement technique that records the mechanical activity of blood circulation characterized by the hydrodynamic pressure within the blood vessels. This method involves the invasive introduction of a pressure sensor, known as a catheter, into the main blood vessels



a) b)

c) d)

Figure 2.1 *Acquisition of electronic signals in the clinical environment: (a) ECG signal, (b) ART signal, (c) ABP signal, (d) FLOW signal; Image retrieval [S1, S2, S3, S4]*

- Non-invasive Blood Pressure (ABP) [20], Figure 2.1 c) – a measurement technique that records the mechanical activity of blood circulation characterized by the hydrodynamic pressure exerted on the walls of blood vessels. This contact technique involves placing a pressure sensor within an elastic cuff that wraps around major blood pressure vessels. From a physical perspective, the pressure values recorded with this technique are similar to those obtained using the invasive method, even though the techniques differ.

- Blood Flow (FLOW) [21], Figure 2.1 d) – a measurement technique that records the mechanical activity of blood circulation characterized by the blood flow within blood vessels. This contact technique involves placing a piezoelectric sensor near major blood vessels. Using the Doppler method, blood velocity is determined as the primary parameter required for calculating the blood flow in question.

2.1 Synchronization of cardiovascular signals

The previously mentioned signals associated with cardiovascular activity follow a certain sequence in terms of waveform. Historically, their periodic evolution is defined during two cardiac phases. These delimited periods originate from the behavior of the heart, whose primary role is blood pumping [29,30]:

- The systolic period - delimits the contraction time of the ventricles of the heart which aim to inject blood volume into the peripheral circulation but also into the pulmonary circulation. Simultaneously with this phase, the atria of the heart are in the process of relaxation with the aim of taking over the blood volume coming from the pulmonary circulation.

- Diastolic period – delimits the relaxation time of the heart ventricles after the blood injection phase. This time, the atria of the heart will be in the process of contraction, aiming to resupply the adjacent ventricles with blood volume.

The first iteration of the digram was defined by the American physiologist Carl Wiggers in the 1920s [33, 34], along with the development of measurement methods in the present field. But the technological limitations of those years, such as the response frequency of the measuring equipment, made it difficult to clearly define the synchronization of the signals, leading to systematic errors. In the first instance, the problem was caused by the correct alignment between the start point of the ECG signal and the ART signal. These impediments were solved much later, during the 1980s [35, 36], with the advance of electronic technology and the information.

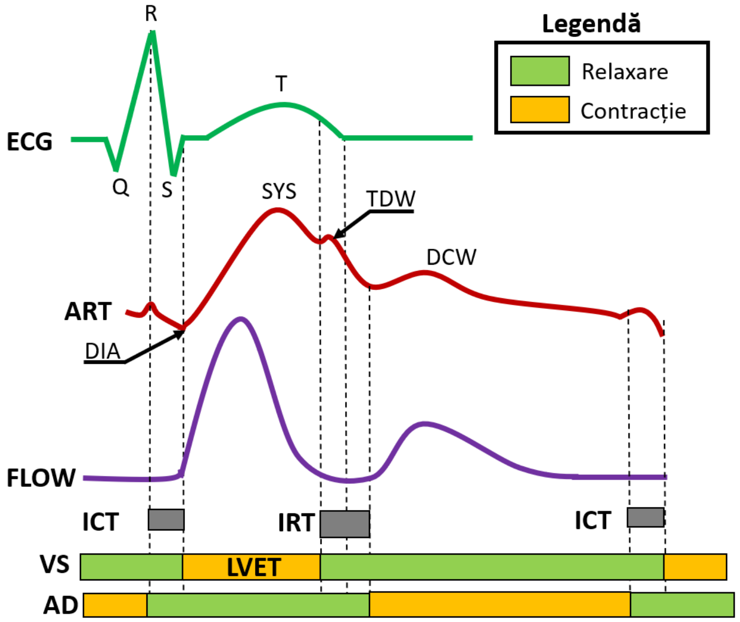


***Figure 2.4** Phases of the arterial cycle and their correspondence with electronic signals.*

2.2 Functional parameters of blood circulation

Experimentally [47,48] it was observed that the blood vessel wall possesses a dynamic coefficient k proportional to the degree of induced deformation, the mechanical stress, which occurs during a cardiac cycle. This behavior comes from the internal structure of the vascular wall, formed by quantified layers of collagen and elastic fibers. The more the degree of mechanical deformation evolves, the more the permissive deformation of the elastic fibers is limited, leading overall to a predominantly rigid behavior of the vascular segment in question. This transition that consumes the available elastic reserve is called the activation of the elastic fibers. Since the activation occurs successively, the coefficient k will evolve in the same way leading to a proportional evolution of the induced arterial pressure, according to the previous equation. It should be noted that in the case of a motor activity such as vasoconstriction, the already activated muscle fibers are equivalent to an additional mass of rigid fibers. This will lead to an early evolution of the induced arterial pressure (purple line) compared to the case of reduced motor activity (blue line), represented by the effect of vasodilatation. In other words, the degree of succession of inflection points is proportional to the ratio between the reservoir of elastic and rigid fibers. The more this ratio is defined in favor of the elastic behavior, the faster the pressure-strain function will evolve.

2.3 Evaluation of flow-pressure relationship based on digital signals

Understanding the parameters that describe cardiovascular functionality is critical in the process of processing the acquired information for medical interpretation. Also, the presence of non-linear behaviors is important to develop algorithms to analyze not only the waveform but also associated numerical values such as maximum arterial pressure and flow velocity. Correspondence between the functioning of the arterial system and the signals originating from this process, whether mechanical in nature or electrically acquired, is also necessary to further develop medical technologies. This aspect will be investigated in detail in the following sections, where the correct extraction of signal features will improve the predictive process regarding health assessment.

Chapter 3

Morphological characterization of the electrical signal of arterial pressure

3.1 Tidal Wave (TDW)

The dynamics of the arterial circulation in conjunction with the biomechanical interfaces, the semilunar valves, will introduce into the morphology of the signal, mechanical or electrical, additional characteristics compared to those presented previously. In this case, a first wave component is called the recoil wave, TDW, as mentioned in the cardiovascular diagram in Figure 2.4. Since in the current literature the origin of this component is a subject still under debate, the present work aims to define a plausible mechanism supported by real scenarios of hemodynamic states. The main goal is to use the obtained model in the future cardiovascular predictions that are the basis of the interpretation of both the ART signal and the one preceded by the PPG type.

3.1.1 The origin of the tidal wave

A first relevant piece of information in deducing the origin of the TDW component, but omitted in the context of biological systems, is the water hammer effect (from the English Water Hammer, annotated WH). This hydraulic effect was first reported by Joukowsky [50, 51], following investigations on the behaviors of liquid and gaseous systems. The phenomenon defines that a sudden change in inertia or fluid flow direction implies the occurrence of a hydrodynamic pressure surplus. In other words, the sudden change in the magnitude of the kinetic energy of the flow will be converted into another form of mechanical energy. In civil fluid transport systems, this phenomenon occurs when valves or distribution valves are closed. The appearance of this effect is undesirable, since the forced conversion of mechanical energy, which implies the appearance of disturbances, leads to the destruction of the walls of the transport tubes. In order to reduce this phenomenon inside rigid systems, special hydraulic elements are used that have in their composition an element with an elastic characteristic so as to mitigate unwanted internal forces.

The Water Hammer effect has two manifestations given by the behavior of the fluid at both ends, downstream and upstream, of the zone where mechanical energy conversion is induced, as illustrated in Figure 3.1. The first manifestation, which occurs in the area upstream of the conversion site, will generate a positive hydrodynamic pressure (+Pw) given by the tendency to agglomerate the liquid volume. The second variation that occurs in the downstream area will generate a negative hydrodynamic pressure (-PW) given by the tendency to rarefy the liquid volume. The elaboration of these two manifestations in the context of biological systems will be analyzed in detail later.

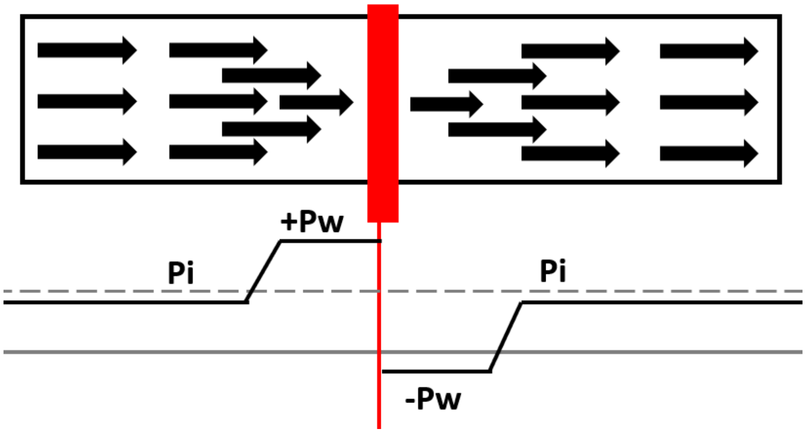


Figure 3.1 *Variations of the Water Hammer effect.*

3.1.2 Characterization of electrical signals in the TDW phase

Another observation regarding this parameter is given by the presence of a trend when it is correlated with the associated systolic value. Thus, a positive type trend is present where the relative amplitude of the flow velocity is proportional to the elevation of the systolic pressure. Since the pressure and blood flow gradient has been shown to be elevated in hypertensive states, the semilunar valves will close earlier than in a normotensive state. Thus, the appearance of TDW will take place at a shorter time compared to the maximum systolic point, which will therefore imply a closer value of the flow velocity in relation to the maximum one.

3.2 Dicrotic Wave (DCW)

The second component present in the waveform of the cardiovascular signals, according to the diagram in Figure 2.4, appears shortly after the previously analyzed one. In specialized literature, two popular names are used: incisura or dicrota [55, 56]; in the present work the term dicrotic component or wave, DCW, will be used. At the moment, the origin of the appearance of this component is still under debate, the mechanism of wave reflection being proposed. In the present paper, an equivalent mechanism will be proposed, since the current one has a low probability of occurrence given the elastic characteristic of the arterial system.

3.2.1 The origin of the dicrotic wave

During the peripheral circulation, the blood flow returns to the heart but in the location of the right atrium. The cyclicity of cardiac activity will involve the phenomenon of atrial contraction shortly after the ventricular ejection phase. In this context, the blood flow in motion is forced to dissipate its inertia as the contracted chamber of the right atrium no longer allows fluid uptake. Thus, from a hydrodynamic point of view, the necessary conditions for the positive WH effect appear. Even if there is no biological valve at the interface between the peripheral arterial circuit and the right atrium, the sudden and temporary interruption of blood flow is sufficient for the effect in question. As a result, the flow is forced to dissipate its current kinetic energy in the immediate vicinity of the system. This phenomenon will lead to the appearance of a positive arterial pressure front, according to Joukowski's theory. To consistently analyze the positive WH effect, physical equations will be defined similar to the TDW case, starting from the mechanical energy conservation theorem.

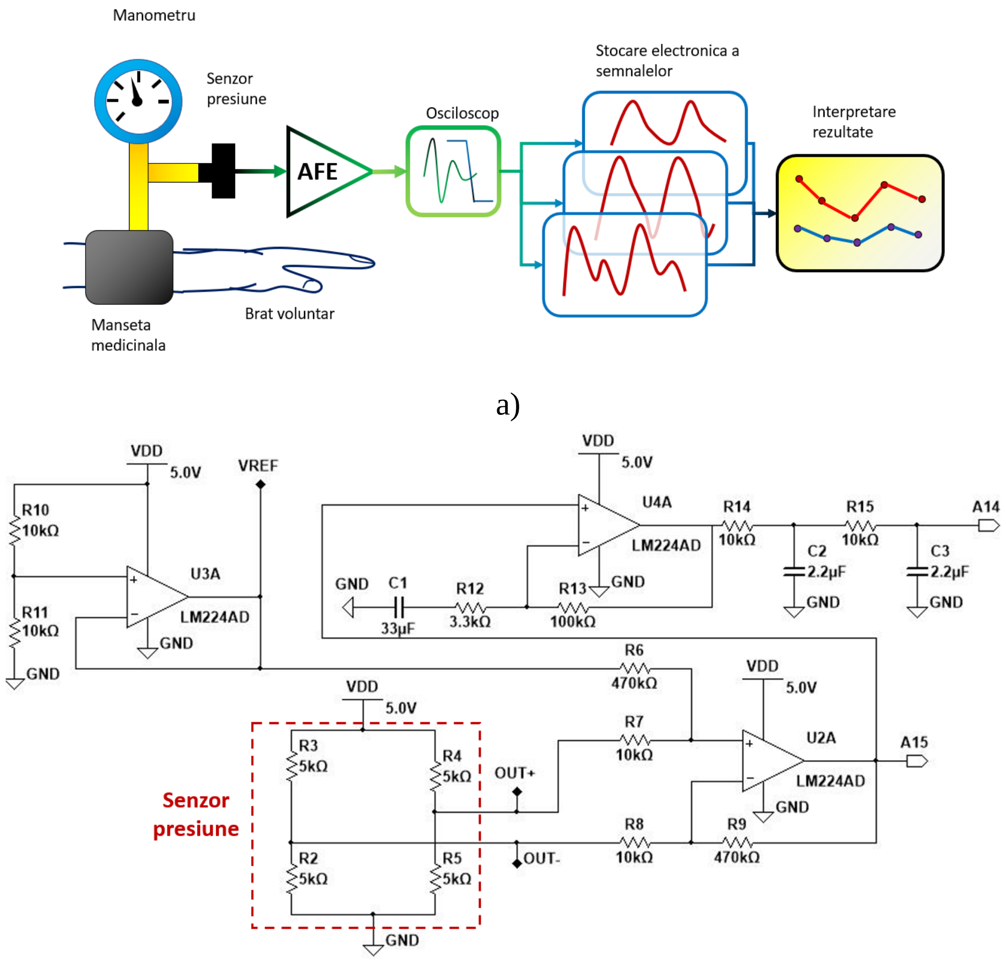
3.2.2 Characterization of electrical signals in the DCW phase

After extracting the relative flow velocity during the DCW phase from each patient and averaging the results, an average of 6.57% of the associated peak-to-peak amplitude is observed. In other words, during the WH effect, the flow velocity tends to a zero value from the initial maximum velocity. This effect is given by the contraction of the right atrium which causes a front to stop the flow of blood towards it. As previously defined, it is observed that the forced stop of fluid inertia (the FLOW signal) leads to the appearance of an arterial pressure surplus (the ART signal). The additional appearance of pressure seen in the ART waveform is the DCW component. As the newly formed pressure tends to subside or dissipate, a further increase in flow velocity is observed based on the morphology of the FLOW signal. The effect comes from the exchange of mechanical energies, so the attenuation of the DCW component will cause a new state of blood flow in the system. The new printed velocity, FLOW_DCW, has a much lower amplitude than that induced by the ventricular ejection effect, thus supporting the proposed mechanical mechanism.

3.3 Variația semnalului sub incidența influențelor externe (compresia artificială)

To test this effect of external influence on a wider spectrum of induced pressure, an equivalent condition experiment was designed. The test method was based on the

Korotkoff technique [60], aiming at the local mechanical behavior of the arterial system. Thus, the measurement procedure as illustrated in Figure 3.13 contains the following steps:



a)

b)

***Figure 3.13** The measurement procedure of the influence of the induced external pressure: a) block diagram of the procedures, b) electrical diagram of the AFE module.*

The AFE module as illustrated in Figure 3.13 b) has the function of amplifying the signal coming from the pressure sensor (illustrated with the red border), attached to the medical sleeve. The conversion between the mechanical and the electrical size takes place by means of the elements placed in the Weathstone configuration, R2 - R5. A fixed voltage value is attached to the differential signal via AO U3A. The reference value is chosen in the middle of the supply range, 2.5 V. This technique is necessary for the next processing block as it is desired to amplify the alternating component of the useful signal and repeat the continuous component. Thus, the configuration of the block that includes AO U4A, has the role of amplifying the AC component by a factor of approximately 34 V/V and only repeating the DC continuous one, amplification factor of 1 V/V. The signal obtained at port A14 is interfaced with the digital oscilloscope input to store the obtained signal.

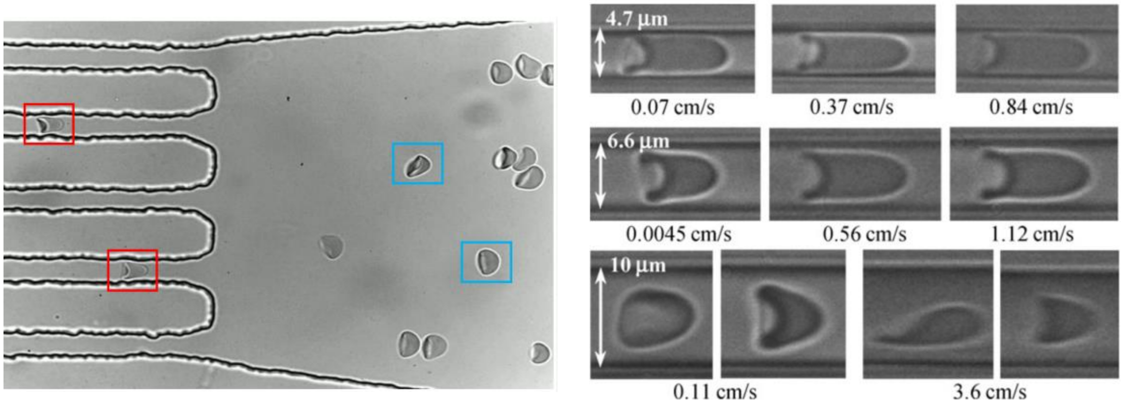
Chapter 4

Optoelectronical signal analysis and processing of the photoplethysmography

The photoplethysmography (PPG) technique is an optoelectronic technology about a century old, first mentioned by the German scientist M.R. Bonsmann in 1934 under the name "photocell method" [63], originally designed for studies in the field of pharmacology. This method is based on an incoherent light source for illuminating human tissue and a photodiode as an optical detector of the light flux after interacting with it. The researcher Alrick B. Hertzman took over this non-invasive technique for investigations in the field of human physiology, especially in the study of peripheral vascular behavior [64, 65].

4.1 Optical model of erythrocite deformation

The settlement according to the velocity profile will subject the entire structure of the erythrocytes to mechanical forces, especially those of deformation. As previously presented, the most important behavior in the present analysis is given by the ability of reversible deformation. Relevant studies [82, 83] have validated this character not only in continuous flow conditions such as the microcirculation regime, but also in transient conditions such as junction areas in the capillary network, Figure 4.6 (a) and (b).

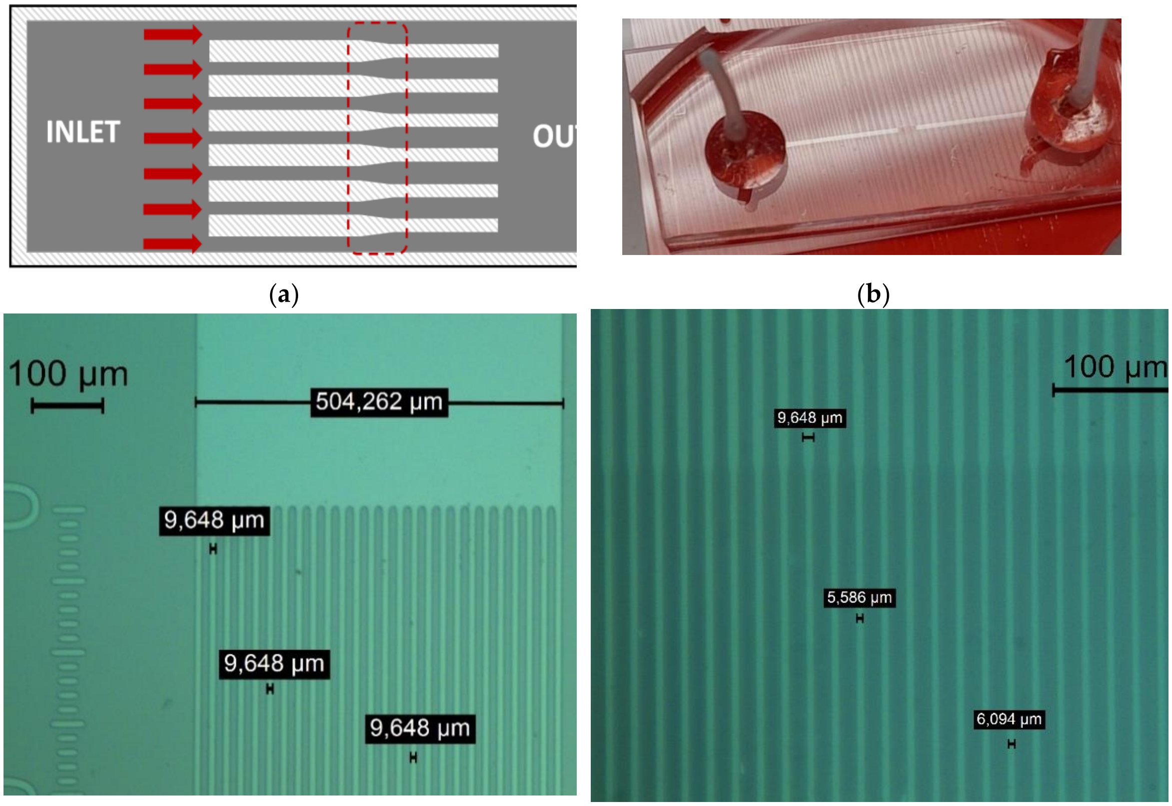


a) b)

Figure 4.6 *Evidence of the deformation of erythrocytes in capillaries: (a) the deformation between the regime of microcirculation (red border) and that of macrocirculation (blue border), (b) the degree of deformation according to the displacement speed and the diameter of the capillary.*

4.1.1 Experimental procedure

To clarify the origin of the PPG signal and define a functional model for this purpose, an experimental study of red cell deformation in a synthetic capillary network, in vitro, was designed [A1]. The synthetic channels were specifically designed to mimic human pathology, with particular emphasis on two widths: 10 µm and 6 µm. A transition zone was incorporated between the regions, illustrated in Figure 4.7 (a) with dashed red border. The length of each channel type was designed to be 500 µm to mimic the size of a real human capillary.



(**a**) (**b**)

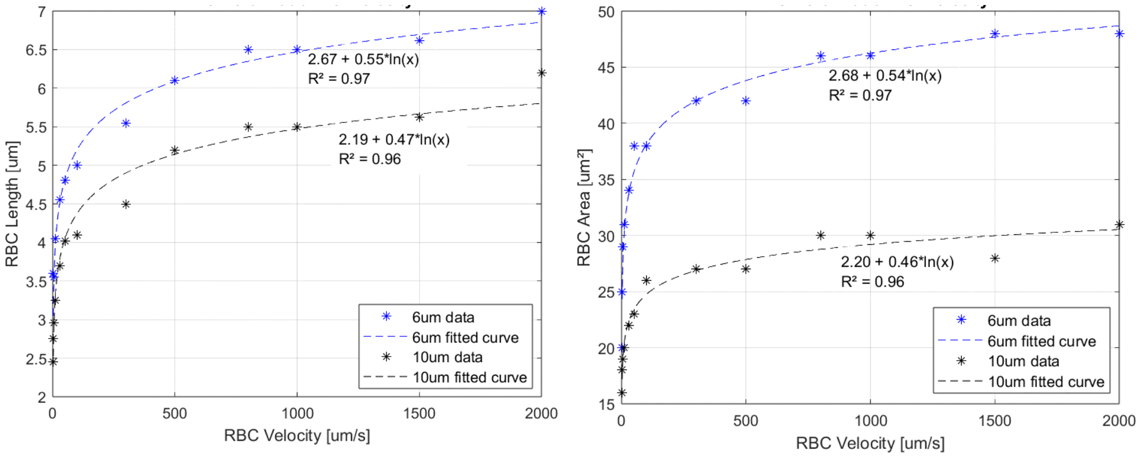
(**c**) (**d**)

Figure 4.7 *Characteristics of synthetic capillary network: (a) model concept, (b) physical implementation result, (c) 10 µm diameter capillary network, (d) 6 µm diameter capillary network.*

4.1.2 Experimental results

The results of the experiment are presented in the form of the deformation behavior, characterized by the final length and the corresponding lateral area with respect to the displacement speed of the RBC. However, due to the erythrocyte clots resulting from the adhesion effect to the PDSM material wall, some microchannels became dysfunctional thus deactivating the presented ROI areas. This unwanted effect increased the initial value of the base speed as the flow rate redistributed to the available paths. Even though this drawback decreased the ability to track the movement of erythrocytes, the experiment was repeated on several sets of microchannels so that sufficient data were collected for the present purpose.

In Figure 4.9 (a), the first significant parameter, the average RBC length, is plotted against the measured flow velocities. It is observed in a first case that the cell elongation conforms to a logarithmic dependence as evidenced by the related interpolation function.

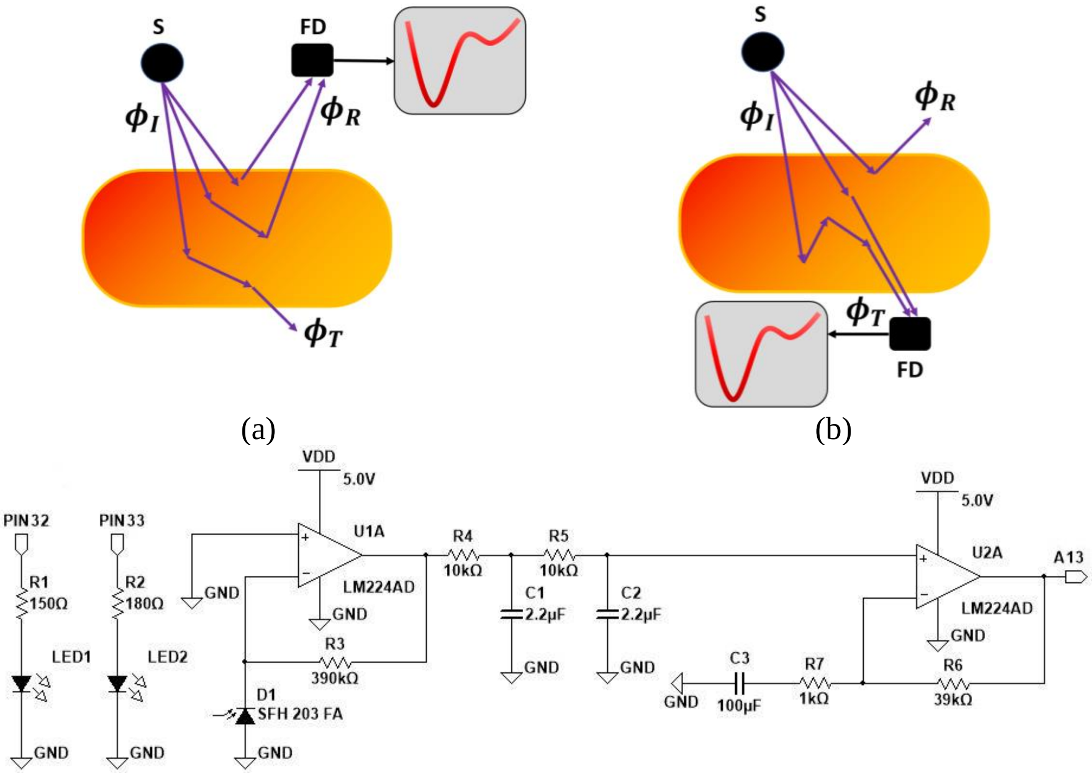


a) b)

Figure 4.9 *Resultant erythrocyte strain function: (a) length strain, (b) lateral area strain.*

4.2 The PPG optical model

The photoplethysmography (PPG) technique is an optoelectronic technology about a century old, first mentioned by the German scientist M.R. Bonsmann in 1934 under the name "photocell method" [63], originally designed for studies in the field of pharmacology. This method is based on an incoherent light source for illuminating human tissue and a photodiode as an optical detector of the light flux after interacting with it. The researcher Alrick B. Hertzman took over this non-invasive technique for investigations in the field of human physiology, especially in the study of peripheral vascular behavior [64, 65]. The PPG sensor can be configured in two ways, depending on the location plan of the two optoelectronic elements in relation to the human tissue, as illustrated in Figure 4.1 a):



(a) (b)

(c)

Figure 4.1 *Architectures of the PPG technique: (a) reflective mode, (b) transmissive mode, c) usual electrical scheme for optoelectronic signal processing.*

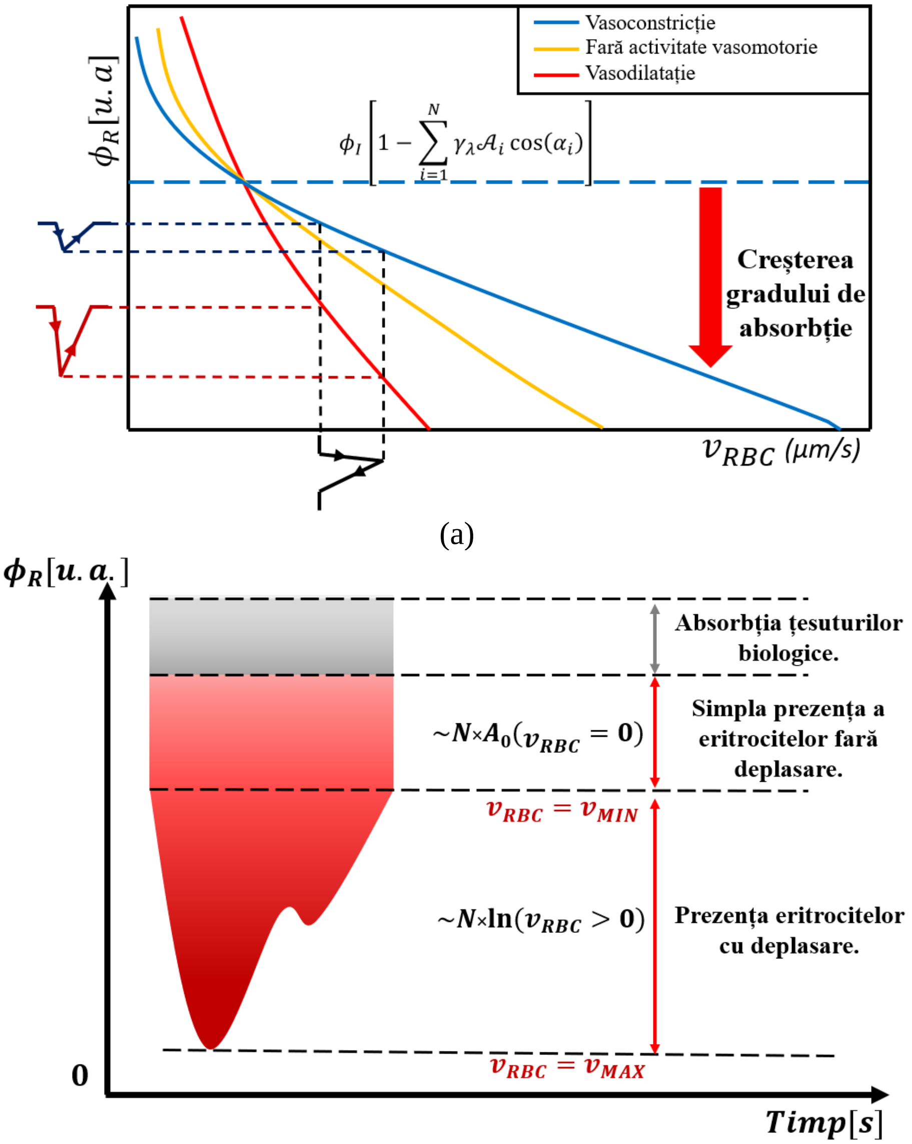
4.2.1 Transfer function

To develop a mathematical model of the PPG technique, the previous results of the practical experiment will be used, but the branch of radiometry from the field of applied physics will also be called upon [91, 92].

The resulting mathematical relationship that defines the correspondence between the mechanical part (deformation) and the optical part (absorption and reflection) is, in fact, a transfer function, as illustrated in Figure 4.11 (a). The number of erythrocytes, usually represented by vasomotor activity, will define the slope of the transfer function. To highlight the contribution of this parameter to the morphology of the PPG signal, two cases were assumed by applying a mechanical stimulus (represented by a black waveform):

- In the case of vasoconstriction (represented by the blue color function), the recorded optical signal will have a reduced amplitude compared to the initial stimulus. This scenario of vasomotor activity has an attenuation effect on the recorded signal. Relevant studies in the field of signal interpretation [98, 99] reported very low PPG amplitudes that lead to the difficulty of a correct detection of the cardiac cycle.

- In the case of vasodilatation (represented by the red color function), the recorded optical signal will have a high amplitude compared to the initial stimulus. This scenario of vasomotor activity has an amplification effect on the recorded signal.



(a)

(b)

Figure 4.11 *Conversion between erythrocyte deformation and resulting PPG signal: a) mathematical transfer function, b) interpretation of PPG signal over time.*

4.2.2 PPG signal desynchronization

The previously presented optical model behaviorally characterizes the physical events in a single capillary. In reality, the present optical technique originates from a fractal effect as follows:

- Each red blood cell is a primary source of associated PPG signal as the degree of deformation is individual.
- Each capillary will in turn have an associated global PPG signal, resulting from the individual but overlapping signals of the RBC transiting it.
- Each region of the peripheral system will in turn have associated a global PPG signal, resulting from the individual but superimposed signals of the capillaries under analysis..

4.2.3 Noise sources in PGG signal

In an ideal case where the peripheral circulation, through the capillary network, is stable and unaltered, the resulting PPG signal will also be stable according to the proposed model equation. As previously discussed, in reality, biological behavior is more complex being given in the first instance by feedback loops.

Analyzing the circulation in a capillary, an effect that takes place during a cardiac cycle and influences the characteristic of the proposed equation is given by the fluctuation of the number of erythrocytes per analyzed volume. Thus, varying the flow rate will not only elongate the original cell shape but also create rarefaction and crowding effects. Before the systolic phase, in the basal velocity state, the erythrocytes will compose a reference density per analysis volume. During the moment of maximum pressure, in the state of maximum velocity, the increased flow will induce a crowding effect, so the density per analysis volume will increase relative to the reference value.

4.3 Similarity between ART and PPG signal

The development of the mechanical model of blood circulation as well as the optical model of photoplethysmography highlight the possible medical applications in the context of digital processing. As the PPG technique has the advantage of being incorporated into wearable devices such as watches or smart bracelets, it can inherit cardiovascular measurements presented in the present work performed with traditional devices. As previously shown, the causal and common parameter for blood pressure and photoplethysmography is blood flow.

Chapter 5

Medical applications based on the PPG technique

5.1 Aplication 1: Determination of left ventricular ejection time(LVET)

The investigations carried out in the present work on the peripheral circulation, by defining a mechanical model and a related optical one, create the basis for the development of medical applications for the purpose of hemodynamic monitoring. As analyzed in the previous chapters, the speed of the blood circulation together with the behavior of the dynamic impedance are the causal factors that lead to the appearance of the ART signal as well as the PPG signal. Thus, between the two types of signals that are measured with electronic techniques, there is exclusively a relationship of correlation and not one of causation. But this statement does not invalidate the PPG technique in extracting cardiovascular information, as argued with the similarity study.

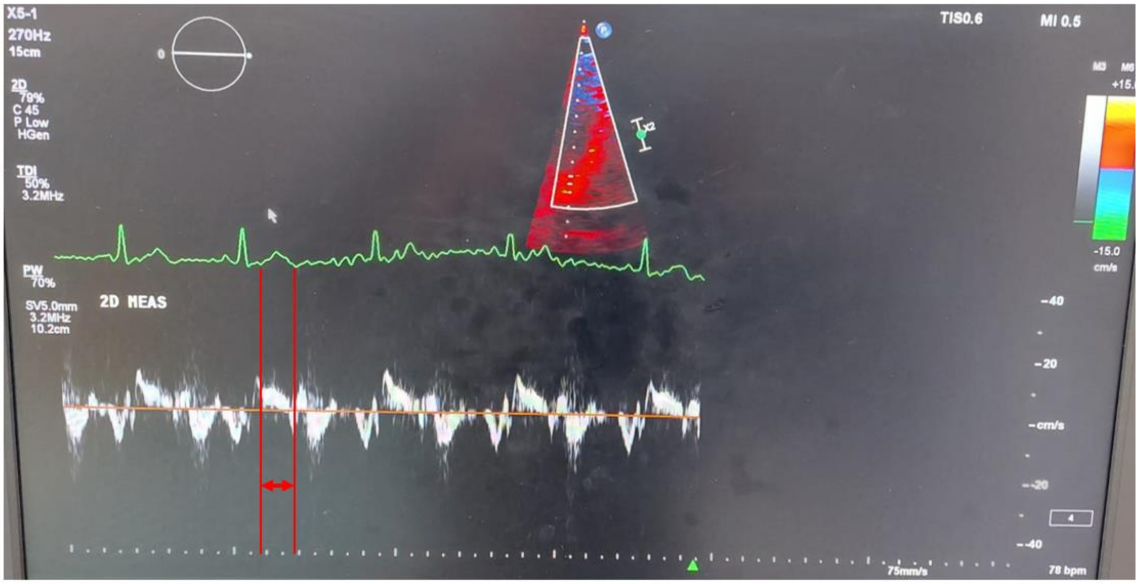


Figure 5.1 *TDI ultrasound capture with ventricular ejection time highlighted (delineation with red lines).*

5.1.1 Defining LVET limits

According to the cardiovascular diagram and those presented previously, the TDW component characterizes the closing activity of the semilunar valves. As an effect, the phenomenon of negative WH will induce a disturbance of the flow speed which will also be reflected on the arterial pressure.

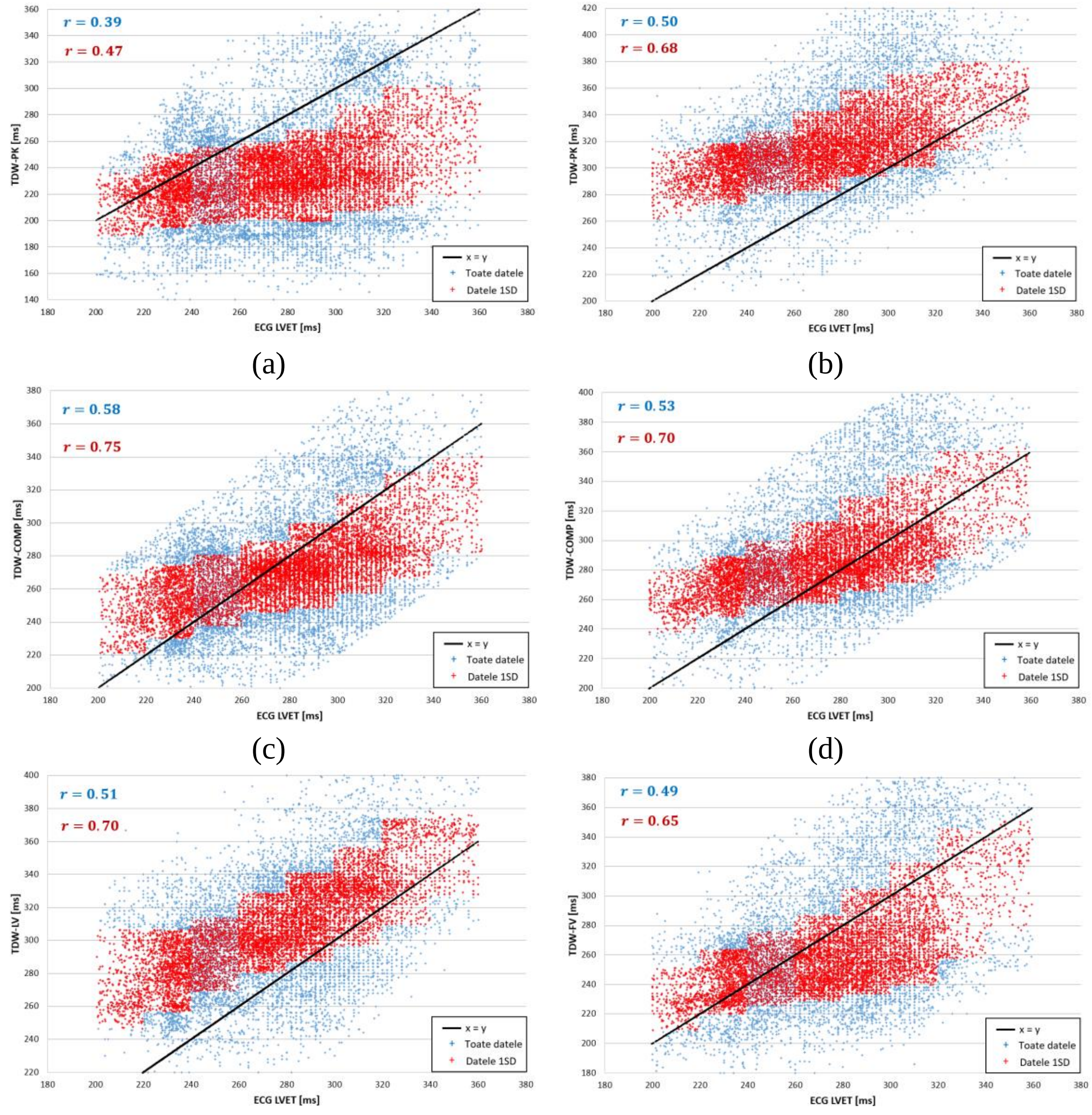
Since based on the ART and PPG signals, the TDW component characterizes the negative WH effect but not the exact moment of semilunar valve closure, all 3 defined points will be analyzed. Additionally, the first point associated with the dicrotic component (NOTCH) will also be considered because in relevant studies it is reported that this parameter actually coincides with the LVET time [107, 108, A4]. In the context of the present work, based on the defined models, this information is invalid, therefore it will be analyzed compared to the TDW parameters.

5.1.2 The results of the LVET determination

The final unified results are presented visually through scatter diagrams, as illustrated in Figure 5.5, and also supported by numerical values, described in Tables 5.1 and 5.2. For a better interpretation of the results, the scatterplot also shows the 1 sigma values (the values that make up a weight of 68% of the total population) on non-overlapping windows of 20 ms duration. Thus, 8 regions are defined in the analysis interval 200 ms - 360 ms. Both data sets are also supported by the Pearson correlation coefficient, highlighted with the associated color.

For the ART signal, the trend of the selected reference points is similar to the intermediate result of the individual cases. The signal component, TDW_PK, underestimates the actual LVET, as shown by the isolated SD values. So, contrary to previously defined expectations, it indicates the non-completion of the closing phase of the semilunar valves. On the other hand, the last component, TDW_LV, forms an overestimated result, which means that the closing phase has already ended. Therefore, in the case of the ART signal, the actual closing time of the semilunar valves is indicated as occurring between the points TDW_PK and TDW_LV. By evaluating the TDW_COMP parameter, the obtained data points have a wide overlap region over the identity line of the LVET. So, by introducing this composite parameter, a better approximation of the exact valve closing moment is obtained. This statement is supported by the Pearson correlation coefficient which reaches the maximum value of 0.58 compared to the performance of the other components. In the case of isolated values with the 1-sigma method, the TDW_COMP parameter obtained an R-factor of 0.70.

For the PPG signal, the consistency of TDW components follows an identical trend as for ART. This time, the first component, TDW_FV, underestimates the actual LVET duration, and TDW_PK has the opposite effect of overestimation. This result is given by the delay effect through the arterial system, so the disturbance detected in the optical signal will manifest much later than that manifested near the heart. Again, the TDW_COMP composite parameter, calculated as the time average of the previously mentioned two points, achieves the maximum performance, with an R-coefficient of 0.53 and 0.70 for 1 sigma values. These results suggest the feasibility of the PPG method for hemodynamic determinations that are characterized in the time domain. The higher performance of the estimation based on the ART signal is predictive in the context of those discussed, since the signal comes from the central area of the arterial network. So, for LVET evaluation using PPG, more attention is needed during the signal processing step to improve the accuracy.



(a) (b)

(c) (d)

(e) (f)

Figure 5.5 *The results of TDW components in the population in relation to the duration of LVET: TDW_PK in (a) ART and (b) PPG, TDW_COMP in (c) ART and (d) PPG, TDW_CV in (e) ART and (f) PPG.*

5.2 Aplication 2: Binary detection of hypertensive state

Another hemodynamic parameter in the evaluation of health status is represented by blood pressure. As discussed in the previous sections, this physical quantity is the result of the interaction between the displacement of the blood mass through the arterial system and the impedance associated with a dynamic characteristic. Blood pressure is monitored in the first instance in the clinical space, especially during surgical interventions, being therefore vital in patient management [109, 110]. Outside of this clinical space, it also represents an important marker for the prevention, detection and evolution of hypertension, a cardiovascular dysfunction characterized by high values of this parameter.

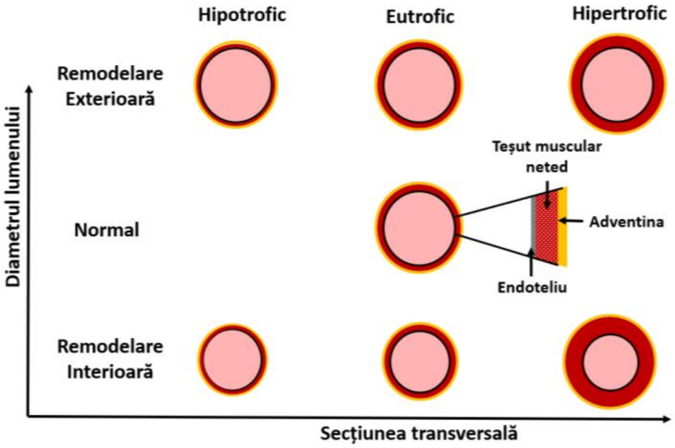


Figure 5.6 *Types of vascular remodeling.*

From a hemodynamic point of view, vascular remodeling represents a change over time in basal arterial impedance. As a result, the associated function will have a different evolution compared to the case of the own arterial network, initially unmodelled. Under the conditions of the presented classes, hypertrophic remodeling represents a quantitative increase in dynamic arterial impedance. Thus, the blood flow that transits the altered system will lead to an increased arterial pressure. In the case of the deficient angiogenesis mechanism scenario, the reduced capillary density is electrically equivalent to the decreased number of resistors in parallel configuration. As a result, the pumping source (the heart) will see an increased work impedance given by the arterial system. In other words, the reduction of the available space (the global volume of the network) necessary for the evolution of the flow, will be reflected by an additional stress exerted on the walls of the blood vessels. Again, the interaction between blood volume and the total impedance of the circulatory system will result in elevated blood pressure.

5.2.1 Quantification of hemodynamic status detection

In order to obtain a wide spectrum of information on the morphological characteristic of the PPG signal,different databases were evaluated. The approach method to develop the desired application was based on the following steps::

- Definition of signal classes by the grouping method according to electronic data observations.
- Pre-evaluation of defined classes in the population for the purpose of possible informational differentiation.
- Evaluation of individual classes simultaneously with preliminary investigations using Machine Learning techniques.

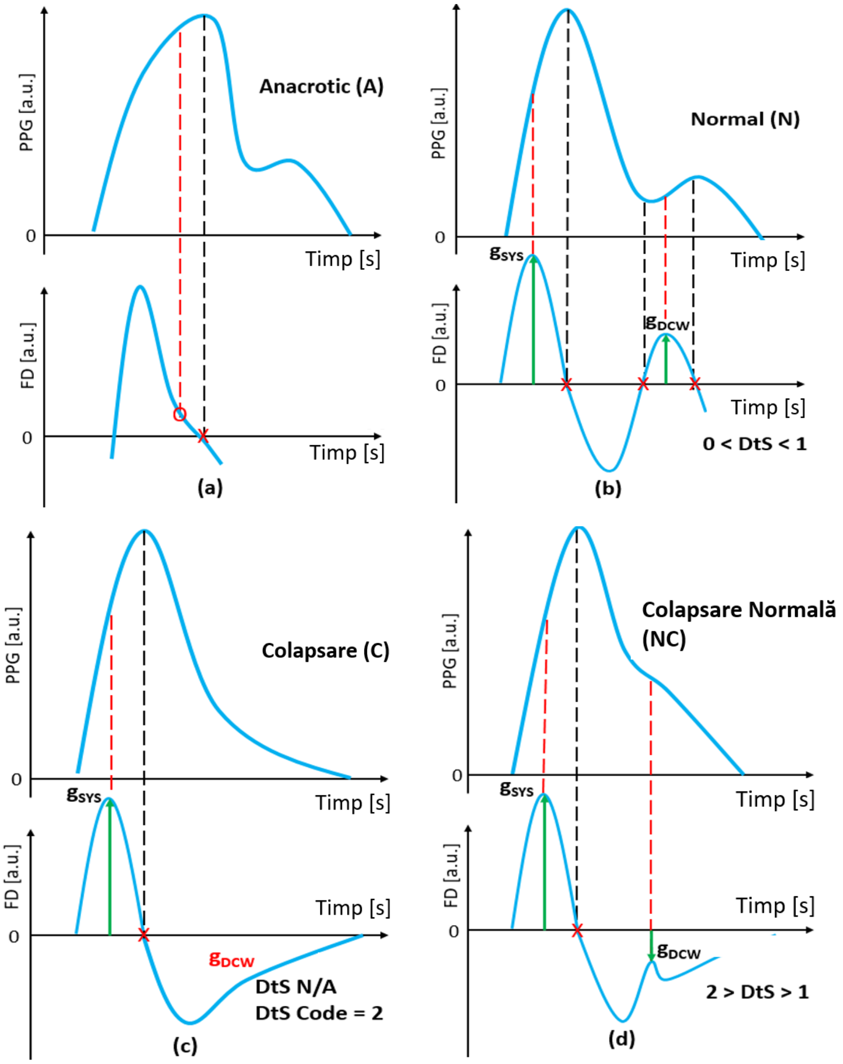


Figure 5.8 *The morphological classes defined based on the signal components: a) class A, b) class N, c) class C, d) class NC..*

5.2.2 Results of binary hemodynamic detection

The evaluation of the hemodynamic status exclusively on the processing of the PPG signal is required to be a relative one within the analyzed signal characteristics. This approach is indicated by the nature of the optical signal simultaneously with its correlation with the hemodynamic information, but of a mechanical nature. Therefore, strictly absolute evaluations in the present context represent an erroneous technique for the evaluation of cardiovascular behavior.

Table 5.7 *The performances of ML architectures in the case of combinations of classes.*

Parameter	**Model**	**Recall [%]**	**Specifity [%]**	**Accuracy [%]**	**Precizion [%]**	**F1 Score**	**AUC**
A, DtS	Ensemble	61	59	62	54	0.58	0.61
NC, DtS	Gaussian SVM	57	62	60	72	0.63	0.58
C, DtS	Gaussian SVM	60	59	58	56	0.58	0.63
A, N	Weighted KNN	56	66	59	81	0.66	0.60
A, N, DtS	Gaussian SVM	61	60	60	58	0.60	0.61
A, NC, DtS	Ensemble	59	59	61	58	0.59	0.60
A, N, NC	Naive Bayes	56	59	58	65	0.60	0.60
A, N, NC, DtS	Ensemble	61	61	63	59	0.60	0.62
A, N, NC, C, DtS	Ensemble	61	61	62	60	0.61	0.60

For the present application, 4 morphological classes were independently defined following the investigation among the population but also following the mechanical analysis regarding the hemodynamic behavior. This technique represents a starting point for the detection of hypertensive episodes that lead to dysfunctional predispositions of the arterial system.

Chapter 6

Conclusions

The present work presented the confluence between the field of information technology, with that of human physiology and applied physics in this regard. Thus, a current and continuously progressing trend was addressed, that of non-invasive electronic technologies for the purpose of health monitoring. This direction is mainly represented by smart wearable devices such as: watches, bracelets, rings and patches. In order to develop information processing algorithms that converge in new medical applications, interdisciplinary investigations and analyzes are needed. The most representative and up-to-date optoelectronic technology in this context is photoplethysmography (PPG).

The ever-increasing maturity of this non-invasive technology leaves room for the research and development of new signal processing techniques including new algorithms for the purpose of the decision factor. In addition, the evolution in the field of sensors and data communication devices paves the way to continuous and non-invasive monitoring of patients in real time. Integrating these technologies into healthcare systems can significantly contribute to improving chronic disease management, reducing costs and increasing access to quality care. However, with all the advantages they bring, non-invasive monitoring technologies also raise certain challenges, such as ensuring data confidentiality, clinical validation and their integration into current medical practice.

In conclusion, this thesis presents original approaches in the field of processing and interpretation of biomedical signals in digital format. The investigations carried out brought a degree of novelty to the understanding of the correlation between cardiovascular behavior and the morphology of the recording waveforms. Also, with the help of the proposed mathematical models, possible medical applications resulting from the PPG technique were defined, with a high degree of confidence..

6.1 Obtained results

The interpretation of digital signals in order to test non-invasive measurement techniques, for the purpose of extracting and interpreting cardiovascular information, was evaluated in stages. Through this type of approach, the origin of the signals associated with the arterial system and their implications for digital processing were presented.

In the second chapter of the thesis, the starting point of the investigation was represented by the interpretation of the electrical signal of arterial pressure (ART). The mechanical information that is digitally translated in the form of an electrical signal presents a unique morphology resulting from the process of blood circulation within the arterial system. Physical parameters representative of this biological process, blood flow, pressure and arterial impedance, modulate the shape of the recorded signal. Thus, a circulatory system characterized by an increased impedance will create a cardiovascular signal not only with a high amplitude, but also with rapid gradients. Analyzing the dependence between the cardiovascular processes and the acquired digital information, both individually and from the findings mentioned in the literature, a mathematical model was defined for the purpose of prediction.

An important result derived from this model is given by the dynamic behavior of arterial impedance. A first characteristic of the non-linear nature is given by the presence of an optimal operating point (circulatory process) so that the blood transport takes place with a degree of maximum efficiency. This non-linear behavior promotes rapid recovery of the circulatory process in case of hemodynamic deficiency. In addition, it also has the role of limiting a possible unfavorable evolution that would lead to critical dysfunctions of the arterial system. Therefore, abstracting the functioning of the circulatory system with the analogy of Ohm's law is fundamentally wrong, neglecting important aspects of it. The causal parameter of the blood circulation process is represented by the flow rate. As a result of the interaction with the dynamic type impedance of the system, the appearance of arterial pressure will also result. In this context, the last parameter will not have the same direction of evolution in relation to the causal one.

In the third chapter, the electrical signal components derived from the mechanical behavior, TDW and DCW, appear following the Water Hammer effect, a superficial phenomenon treated in the literature in the context of elastic biological systems. Understanding the variability of the signal morphology in this context, contributes to the development of new detection and decision algorithms in order to evaluate the hemodynamic state of the patient. External influences such as the respiratory process locally influence the behavior of the arterial system and therefore modulate the shape of the recorded signal. Clear understanding of the resulting morphology is a prerequisite for PPG signal processing for non-invasive cardiovascular monitoring in synergy with wearable technologies.

In the fourth chapter, the origin of the PPG optoelectronic signal was investigated with the support of a practical experiment. Contrary to the current models proposed in the literature, the signal is the effect between the interaction of the incident light with the mechanical deformation of the red blood cells (erythrocytes) strictly in the microcirculation regime. This effect of deformation is reduced with the phenomenon of blood flow in vessels with a diameter larger than the physical size of the globules. The logarithmic law governing this mechanism contains a saturation of strain at higher flow velocities. Therefore, the morphology of the optoelectronic signal is correlated with the hemodynamic behavior by means of a transfer function, defined in the present work. Since each cardiac cycle modulates blood flow differently in accordance with biological feedback loops, the PPG signal will be quasi-steady-state in nature. In other words, during an electronic recording there will not be two periods with identical morphology, characterized from a numerical point of view.

In the last chapter, the intersection of two previously mentioned investigations converged in a pragmatic sense, namely the development of medical applications. By processing and evaluating the information in digital format on different dimensions of analysis, two methods of interpretation of the PPG signal were presented. The first procedure is based exclusively on the temporal dimension, with the objective of determining the ventricular ejection time, a relevant parameter in the characterization of cardiac performance. The use of the optoelectronic signal in this sense presents a high degree of confidence even if certain technical limitations are present. These can be mitigated with advanced signal processing techniques, but as there is no valid system of work steps at the moment, the methods are chosen at will. The second application is strictly based on the morphology of the PPG wave, more precisely on the quantitative characterization of the components, the emphasis being on the dicrotic one. By simultaneously evaluating the variation of this parameter among the population, 4 morphological classes were defined. These represent the input data for an algorithm with Machine Learning architecture, for the detection of hypertensive episodes. The results with a medium degree of confidence suggest the usefulness of the PPG signal for the purpose of the present application, but a refinement of the defined classes as well as the development of a comprehensive database are needed to increase the accuracy.

Based on the published articles that presented a high degree of originality, and the understanding of the phenomena at the border between the interpretation of digital signals and the cardiovascular field, I was selected as a reviewer for prestigious journals (a number of over 15 revisions during the doctoral internship). Also, the scientific contributions made by the present work make the purpose of patent application no. A00063/Feb-2024.

In conclusion, the paper presented new perspectives for processing electrical signals associated with arterial pressure information and photoplethysmography. The origin of the primary wave components was defined in this sense contributing to a clearer understanding of hemodynamic processes. The obtained results represent the basic foundation to define new cardiovascular markers as well as new morphological interpretation techniques in order to improve health monitoring. In particular, there is an emphasis on the development of non-invasive technologies, such as PPG, as its popularity has increased with the upward trend of smart wearable devices.

6.2 Original contributions

During the research for the purpose of this work, significant contributions were made in the field of processing and interpretation of electrical signals associated with the monitoring of human physiology, especially in the hemodynamic and cardiovascular field:

[CO-1] Development of a functional mechanistic model that correlates cardiovascular scenarios with the associated digital ART waveform.
[CO-2] Defining the primary hemodynamic parameters leading to ART signal modulation.
[CO-3] Defining the origin of the signal components, DCW and TDW, which is also reflected in the ART signal morphology.
[CO-4] Characterization of TDW and DCW components for waveform morphology interpretation.
[CO-5] Design and conduct the practical experiment of external induced arterial pressure for the analysis of external influences on digital signal morphology.
[CO-6] Definition of digital data information isolation techniques to reduce systematic errors.
[CO-7] Carrying out the practical experiment, studying the deformability of erythrocytes, in order to understand the origin of the PPG signal.
[CO-8] Development of a functional mechanistic model of the origin of the PPG optoelectronic signal.
[CO-9] PPG waveform characterization resulting from cardiovascular scenarios including understanding of specific morphology.
[CO-10] Definition of a transfer function between the mechanical nature of blood circulation and the optoelectronic nature of the associated signal.
[CO-11] Characterization of technical limitations that contribute to the appearance of systematic errors following PPG signal processing.
[CO-12] Feasibility test run between ART and PPG signal for cardiovascular information extraction by optoelectronic pathways.
[CO-13] Definition of morphological signal classes and analysis of their prevalence in the population.
[CO-14] Design of intellectual property (IP) software algorithms to extract fiducial points of ART and PPG electrical signals.
[CO-15] Design of software algorithms, with intellectual property (IP) status, to determine ventricular ejection time (LVET).
[CO-16] Designing a Machine Learning architecture based on PPG signal, with intellectual property (IP) status, in view of the decision factor on the hypertensive state.
[CO-17] Submission of patent application no. A00063/Feb-2024 [Annex 3] following the acquired knowledge on the optoelectronic field of PPG signal processing and interpretation.

6.3 List of original works

6.3.1 Scientific articles indexed in International Scientific Journals

[A1] Red Blood Cells' Area Deformation as the Origin of the Photoplethysmography Signal,
Evdochim, L (Evdochim, Lucian); Chiriac, E (Chiriac, Eugen) ; Avram, M (Avram, Marioara) ; Dobrescu, L (Dobrescu, Lidia) ; Dobrescu, D (Dobrescu, Dragos) ; Stanciu, S (Stanciu, Silviu) ; Halichidis, S (Halichidis, Stela). Dec 2023 , **SENSORS** . Volume23 Issue23, eISSN.1424-8220, IDS Number AI9A8, DOI 10.3390/s23239515, **WOS:001117942900001**, Five Year **Impact factor 4.1** , ***Category Quartile Q2.***

[A2] Left Ventricular Ejection Time Estimation from Blood Pressure and Photoplethysmography Signals Based on Tidal Wave,
Evdochim, L*;** L. Dobrescu; D.Dobrescu' S.Stanciu; S. Halichidis, Oct 2023 | **APPLIED SCIENCES-BASEL,** Volume 13, Issue 19, eISSN 2076-341, IDS Number U2TQ 9, DOI 10.3390/app131911025, **WOS:001083382900001,** Five Year **Impact factor 2.9, *Category Quartile Q2.

[A3] Hypertension Detection Based on Photoplethysmography Signal Morphology and Machine Learning Techniques,
Evdochim Lucian, Dragoș Dobrescu, Stela Halichidis, Lidia Dobrescu, Silviu Stanciu, **APPLIED SCIENCES-BASEL,** Volume 13, Issue 16, eISSN2076-3417, IDS Number 4B9ZE9, DOI 10.3390/app12168380, **WOS:** 000846124700001, Five Year **Impact factor 2.9, *Category Quartile Q2.***

[A4] Roadmap of Photoplethysmography Technology in Advanced Cardiovascular Assessment,
Lucian Evdochim, Adrian Florescu, Lidia Dobrescu, Romanian Journal of Military Medicine, Volume 127, Issue2, Published Feb 2024, ISSN 1222-5126, eISSN 2501-2312, https://doi.org/10.55453/rjmm.2024.127.5.10, în curs de indexare, Five Year **Impact factor 0.3**

[A5] OSIM: A00063/Feb2024, Senzor neinvaziv pentru estimarea vitezei de curgere sangvină în microcirculație,
Lucian Evdochim

6.3.2 Scientific articles indexed in Clarivate-Web of Science

[B1] Reflection Coefficient in Pressure Pulse of Human Blood Flow,
L. Evdochim; Aleksei E. Zhdanov; Vasilii I. Borisov; D. Dobrescu. 2020 13th International Conference on Communications (COMM). Year: 2020 | Conference Paper | Publisher: IEEE, ISBN 978-1-7281-5611-8, IDS Number BQ6NO, DOI 10.1109/comm48946.2020.9142027, **WOS:000612723900011**.

[B2] Blood Mixers for Transfusion Therapy: Blood Flow Estimation Based on PPG Technique,
L. Evdochim; Aleksei E. Zhdanov; Vasilii I. Borisov; D. Dobrescu; Leonid G. Dorosinsky. 2020 13th International Conference on Communications (COMM). Year: 2020 | Conference Paper | Publisher: IEEE, ISBN978-1-7281-5386-5, IDS Number BQ6NT, DOI 10.1109/comm48946.2020.9142037, **WOS:000612835700069.**

[B3] Blood Mixers for Transfusion Therapy: Method of Blood Flow Velocity Determination Based on Photoplethysmogram,
Lucian Evdochim; Aleksei E. Zhdanov; Vasilii I. Borisov;Leonid G. Dorosinsky. 2020 Ural Symposium on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT). Year: 2020 | Conference Paper | Publisher: IEEE, ISBN978-1-7281-5386-5,IDS Number, BQ6NT, DOI 10.1109/memea49120.2020.9137214, **WOS:000612835700069.**

[B4] OculusGraphy: Ocular Examination for Toxicity Evaluation Based on Biomedical Signals,
Zhdanov, AE; ***Evdochim, L***; (...); Dorosinskiy, LG, 8th International Conference on E-Health and Bioengineering (EHB), 2020 INTERNATIONAL CONFERENCE ON E-HEALTH AND BIOENGINEERING (EHB), ISBN 978-1-7281-8803-4, ISSN 2575-5137, eISSN 2575-5145, IDS Number BR3FU, **WOS:000646194100158.**

[B5] Advanced Electro-Optical Analysis of Photoplethysmogram Signal,
L. Evdochim; D. Dobrescu; L. Dobrescu. 2019 IEEE 31st International Conference on Microelectronics (MIEL), ISBN 978-1-7281-3419-2, ISSN 2159-1660, IDS Number BP8HA, DOI 10.1109/miel.2019.8889633, **WOS:000565455600057.**

[B6] Transmural Pressure Evaluation from Blood Volume Optical Analysis.

Lucian Evdochim; Dragoş Dobrescu; Lidia Dobrescu; Stela Halichidis. 2019 E-Health and Bioengineering Conference (EHB). Year: 2019 | Conference Paper | Publisher: IEEE.**,** ISBN 978-1-7281-2603-6, ISSN 2575-5137, eISSN 2575-5145, IDS Number BP5YO, DOI 10.1109/ehb47216.2019.8969929, **WOS:000558648300061.**

6.3.3 Scientific articles indexed in other BDI databases

[C1] Dicrotic Notch Detection in Various Photoplethysmography Signals Morphologies, ***Lucian Evdochim*;** Dragos Dobrescu; Lidia Dobrescu; Alexandru Florin Săvulescu; Stela Halichidis. 2022 E-Health and Bioengineering Conference (EHB). Year: 2022 | Conference Paper | Publisher: IEEE, ISBN 978-166548557-9, DOI 10.1109/EHB55594.2022.9991651, **indexată SCOPUS**.

[C2] Blood Pressure and Photoplethysmography Waveform Classification by Signal's Morphology,
Lucian Evdochim; Aleksei E. Zhdanov; Lidia Dobrescu; Dragos Dobrescu; Anton Yu. Dolganov. 2022 Ural-Siberian Conference on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT). Year: 2022 | Conference Paper | Publisher: IEEE, ISBN 978-166548557-9, DOI 10.1109/EHB55594.2022.9991651, **indexată SCOPUS.**

[C3] Blood Pressure and Photoplethysmography Signal Pairs Characterization by Dicrotic Notch,
Lucian Evdochim; Aleksei E. Zhdanov; Lidia Dobrescu; Dragos Dobrescu; Anton Yu. Dolganov. 2022 IEEE 23rd International Conference of Young Professionals in Electron Devices and Materials (EDM). Year: 2022 | Conference Paper | Publisher: IEEE, ISSN 23254173, ISBN 978-166549804-3, DOI 10.1109/EDM55285.2022.9855034 **indexată SCOPUS.**

[C4] Photoplethysmography Signal Behavior in Relation with External Stimuli: Temperature and Compresion Force,
Lucian Evdochim; Aleksei E. Zhdanov; Lidia Dobrescu; Dragos Dobrescu; Anton Yu. Dolganov. 2022 IEEE 23rd International Conference of Young Professionals in Electron Devices and Materials (EDM). Year: 2022 | Conference Paper | Publisher: IEEE, Conference Proceedings. ISSN 23254173, ISBN 978-166549804-3, DOI 10.1109/EDM55285.2022.9855035, **indexată SCOPUS.**

[C5] Data Analytics of BP-PPG Dataset: Noninvasive Blood Pressure Assessment by Using Photoplethysmography Fiducial Points,
Lucian Evdochim; Aleksei E. Zhdanov; Lidia Dobrescu; Dragos Dobrescu. 2022 International Conference on Business Analytics for Technology and Security (ICBATS). Year: 2022 | Conference Paper | Publisher: IEEE, ISBN 978-166540920-9, DOI 10.1109/ICBATS54253.2022.9759027**, indexată SCOPUS.**

[C6] Development of a Weight Sensor Based on Strain Gauge Transducer,
Zhdanov, Aleksei E.; ***Evdochim, Lucian***; Dorosinskiy, Leonid G., IEEE Ural-Siberian Conference on Computational Technologies in Cognitive Science, Genomics and Biomedicine, CSGB 2021Novosibirsk, Yekaterinburg26 May 2021through 28 May 2021Code 170711 ISBN 978-166543149-1, DOI 10.1109/CSGB53040.2021.9496002, **indexată SCOPUS.**

[C7] Electric Drive Control System Based on a Reversible Motor Driver,
Zhdanov, Aleksei E.; Dorosinskiy, Leonid G. Borisov, Vasilii I.; ***Evdochim, Lucian***;
IEEE Ural-Siberian Conference on Computational Technologies in Cognitive Science, Genomics and Biomedicine, CSGB 2021Novosibirsk, Yekaterinburg26 May 2021through 28 May 2021Code 170711
ISBN 978-166543149-1, DOI 10.1109/CSGB53040.2021.9496025, **indexată SCOPUS.**

[C8] Blood Mixers for Transfusion Therapy:Photoplethysmogram application for blood velocity determination,
Lucian Evdochim; Aleksei E. Zhdanov; Vasilii I. Borisov; Dragos Dobrescu; Leonid G. Dorosinsky. 2020 IEEE International Symposium on Medical Measurements and Applications (MeMeA). Year: 2020 | Conference Paper | Publisher: IEEE, **ISBN**978-172815386-5, **DOI** 10.1109/MeMeA49120.2020.9137214, **indexată SCOPUS.**

[C9] Correlation Between Blood Pressure and Body Mass Index for Transfusion Therapy Setup,
Lucian Evdochim; Vasilii I. Borisov; Konstantin E. Negodyaev; Aleksei E. Zhdanov; Leonid G. Dorosinskiy. 2021 Ural Symposium on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT), **ISBN** 978-172817691-8, **DOI** 10.1109/USBEREIT51232.2021.9455034, **indexată SCOPUS.**

[C10] Group Delay Effect Analysis Between Arterial Blood Pressure and Photoplethysmography Waveforms,
Lucian Evdochim, Dragos Dobrescu, Lidia Dobrescu, Silviu Stanciu, Stela Halichidis. 2023 E-Health and Bioengineering Conference (EHB), în **curs de indexare SCOPUS .**

[C11] Elastic Water Hammer Effect in Arterial Network: Origin of the Tidal and the Dicrotic Wave in Blood Pressure Waveforms,
Lucian Evdochim, Aleksei E. Zhdanov, Anton Yu. Dolganov, Lidia Dobrescu, Dragos Dobrescu. 2024 Ural Symposium on Biomedical Engineering, Radioelectronics and Information Technology (USBEREIT), în **curs de indexare SCOPUS .**

6.3.4 Other participation in scientific events

[D1] Advances in Photoplethysmography Signal Processing for Blood Hypertension Management,
Lucian Evdochim, Dragos Dobrescu, Stela Halichidis, Lidia Dobrescu, Silviu Stanciu,
Doctoral Symposium on Electronics, Telecommunications & Information Technology 2023

[D2] 6th International School on Imaging with Medical Applications (SSIMA), September 5th-9th 2022, Oradea, România.

6.4 Prospects for further development

The field of digital biomedical signal processing and interpretation is a dynamic one that constantly introduces new processing algorithms. Also extracting health information and converting it into digital format leads to the development of new sensors and computing architectures..

The interpretation of the electrical signal of the arterial pressure should be investigated in other real scenarios besides the operative ones included in the databases used. This includes pre- and post-operative monitoring where the patient is not under the influence of vasoactive medication. It is also necessary to develop a system of detection of signal components, TDW and DCW, agreed in a first phase by the important players in the given field. Here is also a decision-making factor regarding the evaluation of the hemodynamic state, since the TDW component is not always present in the form of a signal, being undetectable.

The investigations conducted in Chapter 3 on the PPG technique are a starting point for improving the technology. A possible direction is given by the redesign of the optoelectronic sensor so that the sensitivity of the detection of the deformation of erythrocytes through the interaction of light is improved. There is also a need to develop complex algorithms that can detect sensor movements in such a way as to remove signal artifacts from useful information.

Technical limitations that appear within medical applications must be minimized for increased decision-making accuracy. A starting point is the simultaneous evaluation of signal components to detect hemodynamic states and therefore to apply compensation techniques to the recorded parameters.

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