PULSE WAVE SEPARATION: A COMPARISON OF METHODS

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Abstract

In the last years new concepts such as pulse wave analysis (PWA) have emerged to determine cardiovascular risk. In PWA the augmentation of the aortal blood pressure due to reflections in the arterial system is expressed by the augmentation index or the augmentation pressure. One of the drawbacks of these parameters is their dependence on the timing of the reflected pressure waves. This problem can be overcome with the concept of wave separation analysis (WSA), which is carried out in the frequency domain and separates the measured pressure wave into forward and backward going waves. Another method for wave separation is known as wave intensity analysis (WIA), which is based on the methods of characteristics and is operating in the time domain.

The aim of this work is to compare the wave separation analysis method and the wave intensity analysis method by looking at several parameters derived from the separated pulse waves based on a study population of 131 patients.

For the backward pressure wave (P_b) the mean amplitude using WSA is 16.26 ($\pm$5.13) mmHg and with WIA 16.16 ($\pm$5.12) mmHg. The mean reflection magnitude (RM) using WSA is 0.626 ($\pm$0.099) and with WIA 0.616 ($\pm$0.096).

The results of this study give a good basis to fully accept wave intensity analysis as an alternative method to perform pulse wave separation.

Keywords: pulse wave analysis, wave separation analysis, wave intensity analysis

Presenting Author's biography

Bernhard Hametner. He was born in 1982 and grew up in Lower Austria. He studied Applied Mathematics in natural sciences at the Vienna University of Technology with specialization in the field of modeling and simulation. Since 2008 he is a PhD student focused on pulse wave analysis at the Vienna University of Technology and in the Health and Environment Department of the Austrian Institute of Technology.

1 Introduction

In the last years new concepts to determine cardiovascular risk have emerged. Until the end of the last century, the main focus has been on diastolic and systolic pulse pressure, and these values still play a major role in prognostics today. Within the last decade emphasis has been laid on the determination of arterial stiffness and its clinical surrogates using dynamical systems, and the concepts of pulse wave analysis (PWA) and pulse wave velocity (PWV) have come into play, which is also visible in the ESH–ESC (European Society of Hypertension – European Society of Cardiology) guidelines for the management of arterial hypertension [1]. In PWA the augmentation of the aortal blood pressure due to reflections in the arterial system is expressed by the augmentation index (AIx) or the augmentation pressure (AP), which are utilized in the time domain by analyzing aortal pressure signals. One of the drawbacks of these parameters is their dependence on the timing of the reflected pressure waves. This problem can be overcome with the concept of wave separation analysis (WSA), which has been introduced by Nico Westerhof and co-workers already in 1972 [2]. In WSA which is carried out in the frequency domain, aortic pressure and flow signals are used to quantify the total amount of arterial wave reflection. Another method for wave separation has been introduced by Kim Parker and co-workers in 1990 and is known as wave intensity analysis (WIA) [3]. This approach is based on the methods of characteristics and is operating in the time domain.

Both methods are not widely used up to now because of difficulties in the non-invasive assessment of aortic flow waves. In recent studies the measured flow curve has been approximated by a simple triangular waveform or an averaged flow curve [4, 5]. In a 15 year community based follow up study using WSA which has been published at the beginning of this year, it has been shown for the first time that the total amount of arterial wave reflection can predict long-term cardiovascular mortality in men and women independent of arterial stiffness [6]. Therefore it can be expected that pulse wave separation will become more important in the near future.

Most of the recent studies are using WSA in the frequency domain for pulse wave separation. WIA seems to be not widely accepted, one reason could be the lack of a detailed comparison of these two methods. Last year two comparative studies have been published, but one was based only on a single measurement from one patient and the other one was using a model of the arterial circulation and no real life data [7, 8].

The aim of this work is to compare the wave separation analysis method and the wave intensity analysis method by looking at several parameters derived from the separated pulse waves based on a broader study population.

2 Methods

2.1 Data assessment

The measurements were carried out at the department of cardiology in the Paracelsus Medical University teaching hospital of Wels-Grieskirchen in Wels, Austria. They were authorized by the local ethic commission and patients gave informed consent. Overall 131 patients were included in the study, 120 experimentees were male, 11 female. The mean age was 59.3 years with a standard deviation of 11.9 years. The lower age limit was 12 years, the upper one 81 years. The mean peripheral systolic blood pressure was 130.6 mmHg with a standard deviation of 15.0 mmHg, the mean peripheral diastolic blood pressure was 80.9 mmHg with a standard deviation of 9.3 mmHg. More information on the basic clinical data can be found in Tab. 1.

Tab. 1 Basic clinical data, given as:
mean value (standard deviation)

Patients	131
Men/Women	120/11
Age (years)	59.3 (11.9)
Weight (kg)	86.5 (14.3)
Height (cm)	173.9 (9.7)
Heart rate (1/min)	63.5 (9.8)
SBP peripheral (mmHg)	130.6 (15.0)
DBP peripheral (mmHg)	80.9 (9.3)
SBP central (mmHg)	120.0 (14.5)
DBP central (mmHg)	81.7 (9.3)

Pressure and velocity signals were gained using two devices in parallel. Velocity waveforms were measured by Doppler Echocardiography over several heartbeats. Thereafter the waveform for one heartbeat was manually digitalized, trying to follow the sonogram as close as possible. The volume flow needed for WSA is velocity multiplied by the cross sectional area of the vessel. Aortic pressure waves were taken from a SphygmoCor device (AtCor Medical Pty. Ltd., West Ryde, Australia), which synthesizes an aortic pressure wave from a peripheral measured pressure signal. An exemplary central pressure curve and the corresponding flow curve can be seen in Fig. 1.

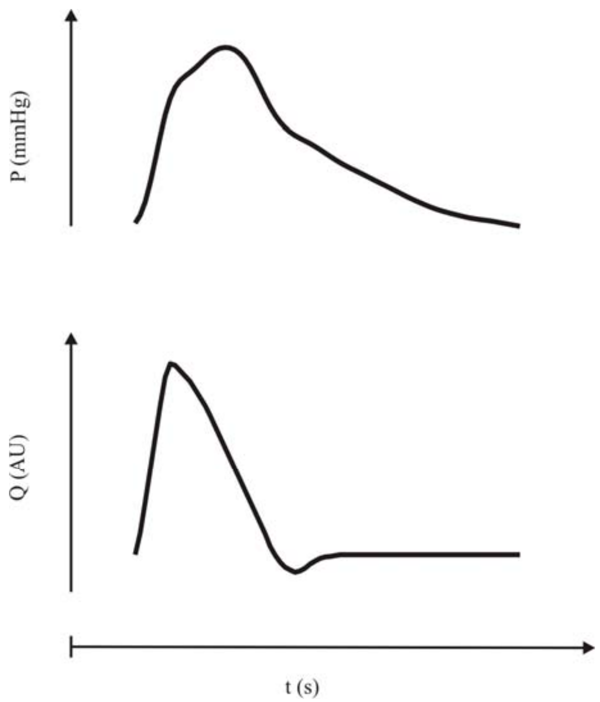

Fig. 1 Central pressure wave (upper figure) and central flow wave (lower figure)

2.2 Impedance wave separation analysis (WSA)

The ratio of pressure (P) and flow (Q) in the frequency domain is called impedance (Z).

$$\frac{P}{Q} = Z \tag{1}$$

Depending on the specific situation, different impedances can be defined [9]. If no reflections are present, the characteristic impedance (Z_c) can be obtained. However the absence of reflections is not true for physiological conditions in the arterial tree. Therefore it is only possible to calculate the so-called input impedance (Z_i).

Following the wave theory, the measurable pressure P_m in the aorta is the sum of forward (P_f) and backward (P_b) going waves [2].

$$P_m = P_f + P_b \tag{2}$$

The same is valid for the corresponding flow waves.

$$Q_m = Q_f + Q_b \tag{3}$$

Subsequently the relationship between pressure and flow can be described as

$$P_f = Z_c \cdot Q_f \tag{4}$$

$$P_b = -Z_c \cdot Q_b \tag{5}$$

So far it is only possible to measure the sum of the forward and backward going waves. To obtain the forward and backward going parts separately in explicit formulas, Eq. (2) – (5) have to be transformed:

$$P_f = \frac{P_m + Z_c \cdot Q_m}{2} \tag{6}$$

$$P_b = \frac{P_m - Z_c \cdot Q_m}{2} \tag{7}$$

To perform the separation, obviously three variables are needed: The pressure and flow in the aorta and furthermore the characteristic impedance which represents the impact of the arterial wall. Z_c is estimated in the frequency domain using the input impedance, which is the ratio of the present pressure and flow. The frequencies in the range of 4 to 10 Hz are taken into account, which is a commonly used span [4, 5, 10, 11, 12]. For higher frequencies there could be inaccuracy due to noise [9]. To minimize the influence of outliers, all input impedances which are greater than a factor of 3 of the median of the considered impedances are not taken into account [7, 13]. It should be noted that the absolute amplitude of Q_m is not relevant for the decomposition. If Q_m is changed by a certain factor, the resulting characteristic impedance will be altered by the same factor in an inverse manner. Thus the calculated waves in forward and backward direction remain unchanged.

2.3 Wave intensity analysis separation (WIA)

The second technique for wave separation is strongly related to the idea of wave intensity [14], even though it is not necessary to calculate the wave intensity for pulse wave decomposition.

WIA has its origin in the development of gas dynamics in the middle of the last century, when new phenomena, particularly shock waves, were detected and had to be explained.

The waves are represented as successive wavefronts which describe the change in properties during a sampling period Δt, exemplarily the corresponding formula for pressure can be seen in Eq. (8). All computations take place in the time domain. These are the main conceptual differences to impedance analysis, where the waves are represented as a sum of sinusoidal waves and the analysis is realized in the frequency domain.

$$dP = P(t + \Delta t) - P(t) \tag{8}$$

Starting point are the Euler equations in one dimension [15]. They involve three state variables, the cross-sectional area of the artery (A), the velocity averaged over the cross-section (U), and the pressure averaged over the cross-section (P). After specifying the relationship between A and P with a so-called tube law equation, the mass and momentum conservation equations can be written in the following form:

$$P_t + UP_x + \frac{A}{A_P} U_x = -\frac{UA_x}{A_P} \tag{9}$$

$$U_t + \frac{1}{\rho} P_x + UU_x = 0 \tag{10}$$

In Eq. (9) and (10) the subscript notation is used for partial derivatives, and ρ stands for the blood density.

The dynamical system can be solved using the method of characteristics introduced by Riemann [16], which leads to the water hammer equations (cf. Eq. (13)). If it is assumed just as in WSA that the forward and backward waves are additive when they intersect, the formula for the changes in forward and backward pressure waves finally can be written as:

$$dP_f = \frac{dP_m + \rho \cdot c \cdot dU_m}{2} \tag{11}$$

$$dP_b = \frac{dP_m - \rho \cdot c \cdot dU_m}{2} \tag{12}$$

Following the notation introduced above, dP_m are differences in the measured pressure over a certain small time interval and dU_m are differences in velocity. The wave speed is denoted by the parameter c.

The wave speed can be determined using the PU-loop method. It is assumed that during the first period of the systole there are only forward going waves present in the artery. Therefore $P_m=P_f$ and the water hammer equation can be written as:

$$dP_m = \rho \cdot c \cdot dU_m \tag{13}$$

The ratio of dP_m and dU_m should be almost the same for the first time steps due to the lack of backward going waves and therefore a value for c can be calculated.

As for the impedance method the magnitude of U_m is irrelevant. A change of U_m by a certain factor would result in a change of c by the same factor in the inverse way. Thereupon this cancels each other in the calculation of the forward and backward travelling waves.

3 Results

In a first step an optical comparison of the obtained forward and backward going pressure waves can be done. In Fig. 2 and Fig. 3 the separated waves for an exemplary patient, using one time WSA and one time WIA, are illustrated. No major differences can be seen.

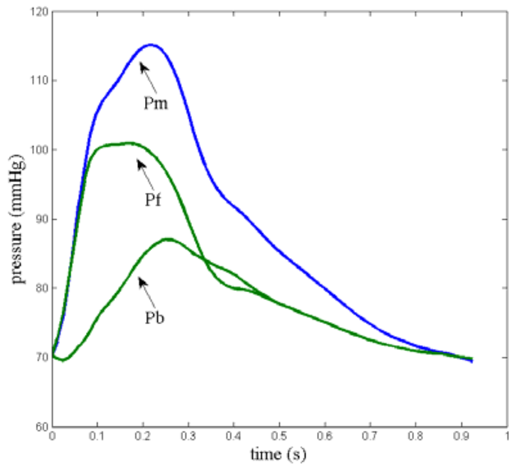

Fig. 2 Separated pulse wave using impedance wave separation analysis (WSA): central pressure wave (P_m), forward wave (P_f), backward wave (P_b)

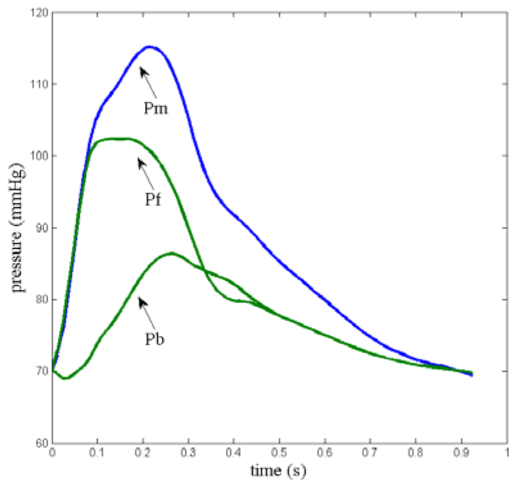

Fig. 3 Separated pulse wave using wave intensity analysis separation (WIA): central pressure wave (P_m), forward wave (P_f), backward wave (P_b)

The amplitudes of P_f and P_b are important parameters to determine the reflections in the arterial system. Based on these amplitudes, two further parameters can be derived, the reflection magnitude (RM) and the reflection index (RI). The reflection magnitude is the quotient of the backward and forward amplitude of the separated pressure waves.

$$RM = \frac{\max(P_b) - \min(P_b)}{\max(P_f) - \min(P_f)} \tag{14}$$

For the reflection index the denominator is changed to the sum of the two amplitudes, see Eq. (15).

$$RI = \frac{\max(P_b) - \min(P_b)}{\max(P_f) - \min(P_f) + \max(P_b) - \min(P_b)} \qquad (15)$$

For the forward pressure wave (P_f) the mean amplitude (standard deviation in brackets) using WSA is 26.15 (7.65) mmHg and with WIA 26.32 (7.45) mmHg. For the backward pressure wave (P_b) the mean amplitude using WSA is 16.26 (5.13) mmHg and with WIA 16.16 (5.12) mmHg.

The mean reflection magnitude (RM) using WSA is 0.626 (0.099) and with WIA 0.616 (0.096). For the reflection index (RI) the mean value using WSA is 0.383 (0.039) and with WIA 0.379 (0.038).

The correlation between the two methods is 0.991 for P_f and 0.998 for P_b.

4 Discussion

The analysis of the results of the wave separation using the two different methods of wave separation analysis and wave intensity analysis show small deviations in the waveforms of the forward and backward going waves. This is mainly based on the different determination of the wave speed and characteristic impedance respectively. Overall the small differences in the waveform do not have a major impact on the derived parameters. This can be seen in the comparison of the mean parameter values as well as in the correlations which are above 0.99 for the amplitudes of P_f and P_b. For the amplitude of P_b and for RM the scatter plots can be seen in Fig. 4 and Fig. 5, for the amplitude of P_f and for RI the plots look quite similar and are omitted therefore.

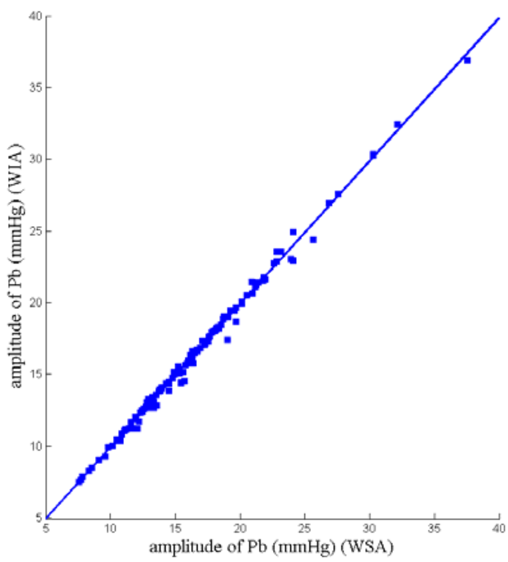

Fig. 4 Scatter plot of amplitude of backward going pressure wave (P_b), calculated using wave separation analysis (WSA) and wave intensity analysis (WIA)

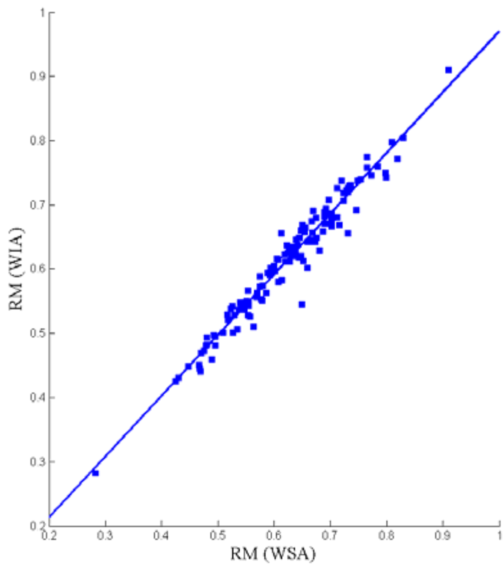

Fig. 5 Scatter plot of reflection magnitude (RM), calculated using wave separation analysis (WSA) and wave intensity analysis (WIA)

4.1 Bland-Altman analysis

To detect systematic differences of the two methods a Bland-Altman analysis is performed. The results are satisfying for all parameters under investigation. The mean differences are close to zero for all parameters and the standard deviations are in a narrow range. Furthermore no specific trends in the Bland-Altman plots could be detected. In Fig. 6 and Fig. 7 the results are visualized for P_b and RM again.

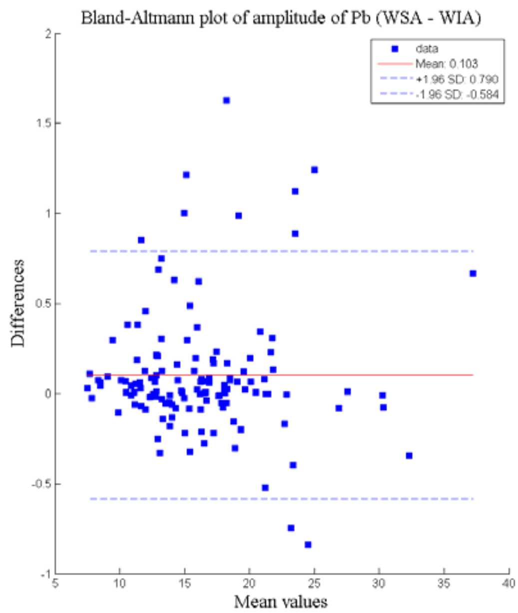

Fig. 6 Bland-Altman plot of amplitude of backward going pressure wave (P_b), calculated using wave separation analysis (WSA) and wave intensity analysis (WIA)

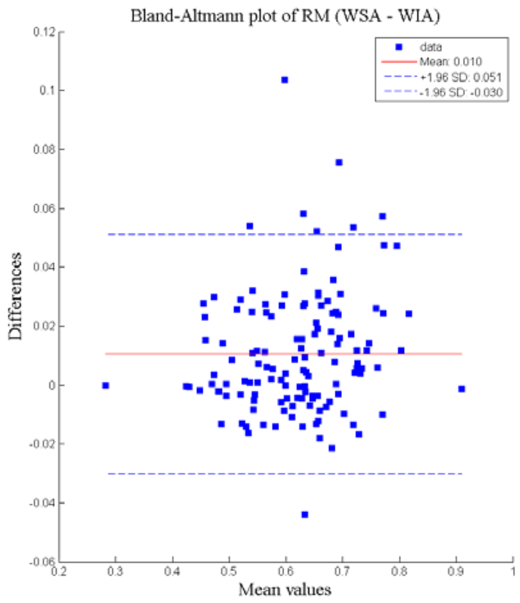

Fig. 7 Bland-Altman plot of reflection magnitude (RM), calculated using wave separation analysis (WSA) and wave intensity analysis (WIA)

4.2 Limitations

In this study flow waveforms derived from sonogram measurements have been used for pulse wave separation. As described above, in recent studies artificially produced waveforms have been used for the separation, which haven't been tested in this study.

Both methods, WSA and WIA, are applied in one specified way. But both can be altered without changing the procedure per se, which might lead to other results. For WSA it is mainly the range of the frequencies taken into account for the estimation of the characteristic impedance that could be modified. For WIA there exist other ways to estimate the pulse wave velocity, particularly a so-called sum of squares method.

4.3 Conclusion

The results of this study give a good basis to fully accept wave intensity analysis as an alternative method to perform pulse wave separation and underline the recently published statements of the comparability of these two methods. To get insight in the comparability of WSA and WIA for artificially generated flow curves, further investigations should be done.

5 References

[1] G. Mancia, G. De Backer, A. Dominiczak, R. Cifkova, R. Fagard, G. Germano, G. Grassi, A.M. Heagerty, S.E. Kjeldsen, S. Laurent, et al. 2007 Guidelines for the management of arterial hypertension-The task force for the management of arterial hypertension of the European society of hypertension (ESH) and of the European society of cardiology (ESC). *European Heart Journal*, 28:1462–1536, 2007.

[2] N. Westerhof, P. Sipkema, G.C. van den Bos, and G. Elzinga. Forward and backward waves in the arterial system. *Cardiovascular Research*, 6:648–656, 1972.

[3] K.H. Parker and C.J.H. Jones. Forward and Backward Running Waves in the Arteries: Analysis Using the Method of Characteristics. *Journal of Biomechanical Engineering*, 112(3):322–326, 1990.

[4] A. Qasem and A. Avolio. Determination of Aortic Pulse Wave Velocity From Waveform Decomposition of the Central Aortic Pressure Pulse. *Hypertension*, 51(2):188–195, 2008.

[5] J.G. Kips, E.R. Rietzschel, M.L. De Buyzere, B.E. Westerhof, T.C. Gillebert, L.M. Van Bortel, and P. Segers. Evaluation of Noninvasive Methods to Assess Wave Reflection and Pulse Transit Time From the Pressure Waveform Alone. *Hypertension*, 53(2):142–149, 2009.

[6] K.L. Wang, H.M. Cheng, S.H. Sung, S.Y. Chuang, C.H. Li, H.A. Spurgeon, C.T. Ting, S.S. Najjar, E.G. Lakatta, F.C.P. Yin, et al. Wave Reflection and Arterial Stiffness in the Prediction of 15-Year All-Cause and Cardiovascular Mortalities: A Community-Based Study. *Hypertension*, 55(3):799–805, 2010.

[7] A.D. Hughes and K.H. Parker. Forward and backward waves in the arterial system: impedance or wave intensity analysis? *Medical and Biological Engineering and Computing*, 47(2):207–210, 2009.

[8] J.P.H.M. van den Wijngaard, M. Siebes, and B.E. Westerhof. Comparison of arterial waves derived by classical wave separation and wave intensity analysis in a model of aortic coarctation. *Medical and Biological Engineering and Computing*, 47(2):211–220, 2009.

[9] W.W. Nichols and M.F. O'Rourke. *McDonald's Blood Flow in Arteries*. Arnold, London, 4th edition, 1998.

[10] A. Swillens and P. Segers. Assessment of arterial pressure wave reflection: methodological considerations. *Artery Research*, 2(4):122–131, 2008.

[11] B.E. Westerhof, I. Guelen, N. Westerhof, J.M. Karemaker, and A. Avolio. Quantification of wave reflection in the human aorta from pressure alone: A proof of principle. *Hypertension*, 48(4):595–601, 2006.

[12] P. Segers, E.R. Rietzschel, M.L. De Buyzere, D. De Bacquer, L.M. Van Bortel, G. De Backer, T.C. Gillebert, and P.R. Verdonck. Assessment of pressure wave reflection: getting the timing right! *Physiological Measurement*, 28(9):1045–1056, 2007.

[13] P. Segers, E.R. Rietzschel, M.L. De Buyzere, S.J. Vermeersch, D. De Bacquer, L.M. Van Borte, G. De Backer, T.C. Gillebert, and P.R. Verdonck. Noninvasive (Input) Impedance, Pulse Wave Velocity, and Wave Reflection in Healthy Middle-Aged Men and Women. *Hypertension*, 49(6):1248–1255, 2007.

[14] K.H. Parker. An introduction to wave intensity analysis. *Medical and Biological Engineering and Computing*, 47(2):175–188, 2009.

[15] L. Euler. Principia pro motu sanguinis per arterias determinando. *Opera Posthuma*, 2:814–823, 1844.

[16] B. Riemann. Über die Fortpflanzung ebener Luftwellen von endlicher Schwingungsweite. *Abhandlungen der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, 8:43–65, 1860.