THE EVALUATION OF ARTERIAL PULSES, ROLE AND CLINICAL IMPORTANCE

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Dedication

This short and incomplete review of some own interests and some outlooks is dedicated to

Bohumil Fišer

who, together with all members of the “Brno Team”, organized and stimulated so many interesting ideas and meetings, and who, together with all friends in this city, made Brno to a meeting point, where all of us love to come together.

It seems to me that many ideas and plans, on which all of us sometime started to work and which then were forgotten or neglected, suddenly come up again, so that even some historical parameters have recently received a kind of scientific medical OSCAR, which is entitled “GOLD STANDARD”.

I would say that exclusively Bohumil and all members of the „Brno Team“ deserve such a “Gold Standard” title.

Below I will try to present my opinion that I have doubts about the validity of all other “gold standard” titles in medical science.

A b s t r a c t

Quite some time after the periods of Otto Frank, Philipp Broemser, and Erik Wetterer – whom I can call my teacher and who wrote a book on the arterial pulse together with me – the interest in arterial hemodynamics appeared not really of importance in medicine.

Recently fluid dynamics of the cardiovascular system and, in particular, the generation of arterial pressure and flow pulses have gained more and more interest. Parameters and mathematical variables were rediscovered or reinvented and several types of indices were constructed. The computerization finally permitted easily to estimate and calculate parameters and indices. And of course, competition between different types of instrumentation plays a role, even as far as normal values of parameters and indices are concerned. Funny enough, as a consequence, certain parameters and measurement techniques are being revalued as “gold standard”.

In this short study it is attempted to summarize some basic facts of cardiovascular fluid dynamics. Furthermore it is attempted, as short as possible, to explain the two ways to describe signals: in the way of time domain and in the way of frequency domain.

K e y w o r d s

Pulse wave velocity, Pressure-flow relation, Wave reflection, Arterial pulse

REMARKS

The choice of words, which are used in order to express certain thoughts, gives insight into unconscious trends of brain activity.

I am astonished by the increasing abundance of expressions like "gold standard" in medicine and medical research. One interesting explanation of using such an expression can be found in Sigmund Freud's book on "jokes and their relation to the unconscious".

There appear to me two main considerations for an analysis. At first the jealous association of medicine with gold and money may play a role. In fact, this is in agreement with the observation of a present trend in clinical medicine towards business-like industrialization (*5*). On the other hand it seems surprising that in the current time of financial and banking crisis, the rather slippery and variable gold value is chosen for the description of biological norms and standards. Perhaps unconsciously the word gold expresses the wish that life should not be associated with the uncertainties of international oil corruption.

One such "gold standard" supposedly is the value of the pulse wave velocity for the estimation of the stiffness along the aorta as measured between carotid and femoral arteries (*9*).

INTRODUCTION

The time course of functional processes in a dynamic system – like the CV system – depends on the structure of the system. Therefore, one can state that the observation of functional processes can be used to extract diagnostic information about structure and function.

The functional processes of the CV system are related to flow and pressure in the vascular channels.

This trivial introduction aims at the question how to extract relevant diagnostic information, and how to analyze and present this information.

Any time-dependent signal – like arterial pulses – can be analyzed and described in terms of time domain or in terms of frequency domain.

The time sequences of arterial pressure and flow are described mathematically by a pair of transmission equations. These equations have been used already in the 19th century by E.H. Weber, by A.I. Moens, and by J. v. Kries.

When I read about hemodynamic recordings, interpretations and calculations I have the feeling that experiments and descriptions should be revisited, which Wetterer and Kenner published in 1968 in a book which had the disadvantage of having been written in German and which in addition has been unavailable since many years. These experiments and explanations were easy to understand and were intended to present some basic knowledge about developments in the analysis of arterial pulses in a simple form.

The following is an attempt to review and to explain some fundamental facts which seem essential to me for application in diagnostic procedures.

TIME DOMAIN

Pulse wave velocity

The pulse wave velocity is an essential term in these equations. The equation which describes the pulse wave velocity as a function of the physical properties of an elastic tube and the contained fluid bears the name of Moens' equation:

$$c = \sqrt{Eh/2r\rho}$$

c: pulse wave velocity, E: elastic modulus, h: wall thickness, r: radius of the tube, ρ: density of the fluid

The pulse wave velocity in a tube increases with increasing elastic modulus (a measure of stiffness) and with wall thickness. c decreases with increasing radius and increasing density of the fluid (blood).

Due to the tissue properties, distension of arteries – by increasing blood pressure – increases the elastic modulus and consequently the pulse wave velocity.

Characteristic impedance

For illustration of the behavior of pulse waves in an artery, Wetterer and Kenner used a model system consisting of a pump and an elastic tube, which on its distal end is adjusted with an outflow resistance. In the example of *Fig. 1* the pump generates a flow pulse. The pressure reacts with a pressure pulse. As will be shown below, such a pump like a normal ventricle may be called a "hard" pump. During the diastole the outflow valve is closed, consequently no central flow can be seen during this period.

The relation between the amplitude of the pressure pulse (dp) and the flow pulse (dq) is described by the so-called characteristic impedance

$$Z = dp/dq$$

Z can be determined by the following relation:

$$Z = c\rho/r^2\pi$$

The stiffer the artery and the higher the pulse wave velocity, the higher is the pressure amplitude – in relation to a given flow amplitude.

Pulse wave reflection

Pressure and flow waves run along a fluid filled tube with the velocity c. On a location where the characteristic impedance increases or decreases or where a resistance is located, wave reflection takes place. The reflected part of a wave then runs into the reverse direction. In the arterial system the main peripheral reflections are positive, thus the pressure wave returns without changing the sign, as in the simple example of *Fig. 1* (from *Wetterer and Kenner,* p. 28).

If a reflected wave reaches the closed outflow (e.g. aortic) valves, then total reflection takes place – as can be seen in *Fig. 1*.

Fig. 1
Central flow pulse (bottom) and positive end-reflection of pressure pulses. i flow, M pressure (central, middle, end of tube)

As long as the valve is open through the systole, the reflection factor may be reduced. The reflection factor k indicates the sign and magnitude of the reflected part of the wave as related to the incoming magnitude. The following equation describes the reflection factor at the location of resistance:

$k = (R - Z)/(R + Z)$

The equations include the description of the reflection of both pressure and flow waves. It was Ph. Broemser who recognized the fact that the returning reflected pressure wave may influence the ejection of the corresponding ventricle. He was the first to discuss the possibility of an optimal matching between the heartbeat and the structure of the vascular system.

Pressure-flow relation and wave reflection

A resistance R is defined as the quotient of pressure gradient and flow gradient. From the observation of a typical pressure-flow relation it can be concluded that at any point of the function shown in *Fig. 2* (from *Wetterer and Kenner,* p. 316) – according to the given definition – R may have a different value for different pressure values. It was to my knowledge R. Ronniger (*7*) who recognized that for the peripheral reflection of a wave the steepness of the pressure-flow relation in the range of the pressure amplitude is essential:

$R_{diff} = dp/dq$

The fact that the pressure-flow relation is not proportional, but may be nonlinear and may be described by a non-proportional line, is important for the actual values of systolic and diastolic pressure as indicated in *Fig. 2*. It can be concluded that the reflection factor and the magnitude of peripheral reflection are not necessarily related to the value of the total peripheral resistance.

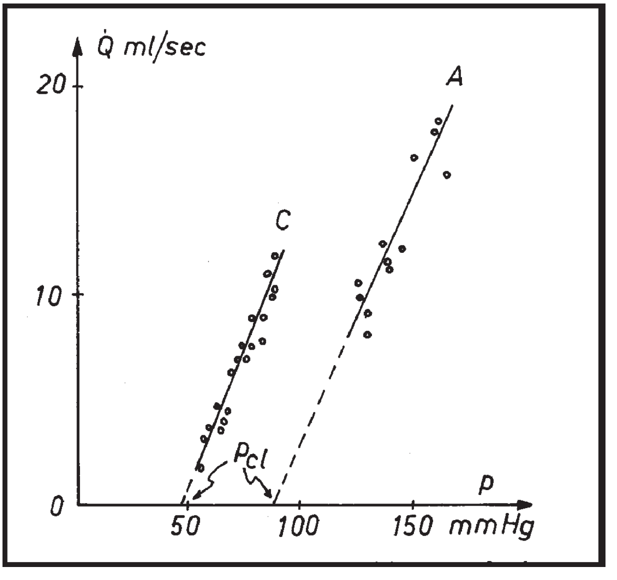

Fig. 2
Non-proportional pressure (p) – flow (Q) – relation in an anesthetized dog. C control, A after Adrenalin infusion

Negative reflection

There are two interesting conditions where negative reflection takes place.

One condition is present when – e.g. in the upper extremity – a reflected wave runs towards the branching point at the aorta. At this point the reflected wave finds – entering the aorta – a marked decrease of the characteristic impedance. Therefore, this wave is negatively reflected. It returns in distal direction after changing its sign.

Another condition is artificially produced by the inflation of a cuff during the classical measurement of blood pressure. The location of the artery, which is occluded by the inflated cuff, has an effect as a positive reflection site. During the following reduction of the cuff pressure, the arterial pressure wave may suddenly open the occluded artery, thus generating an effect which corresponds to a sudden shift from positive to negative reflection at this location (*3*). In any location and/or condition of the body where arteries are compressed by outside pressure, similar phenomena may be present.

Hard (flow) and soft (pressure) pump

Fig. 3 (from *Wetterer and Kenner,* p. 185) explains the difference between the extreme types of the pumps. A normal strong ventricle generates flow pulses even against increasing outflow resistance. It rather corresponds to a "hard pump". In contrast, a ventricle in a state of decompensation reacts markedly towards changes of outflow resistance. It rather can be compared to a soft pressure pump. In the case of a hard pump retrograde incoming waves, which arrive at the root of the aorta during a systole, are reflected positively. In the case of a soft pump, during the systole the reflection factor is reduced or even a negative central reflection can be expected.

These considerations explain the fact that the properties of the heart muscle have a characteristic effect on the central aortic pulse contour.

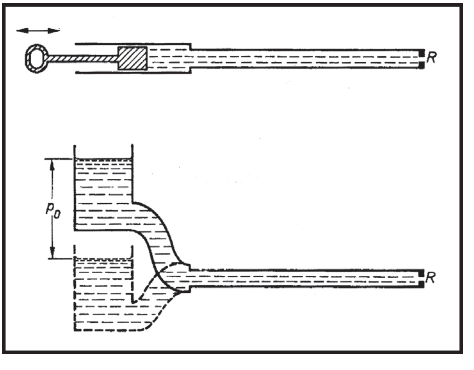

Fig. 3
"hard" flow pump
"soft" pressure pump

FREQUENCY DOMAIN

Resonance and transfer function

If, into the elastic-tube model, instead of periodic pulses of a certain frequency, sinusoidal flow oscillations of variable frequency are generated by the pump, then resonance phenomena can be observed as shown in *Fig. 4* (from *Wetterer and Kenner,* p. 60).

It is evident that a peripheral pressure contour has a different shape than a central (aortic) pressure pulse.

In the case of sinusoidal pressure variations, the shapes of flow and pressure are always and everywhere sinusoidal. Besides by frequency, central as well as peripheral oscillations can be characterized (1) by amplitude and (2) by phase.

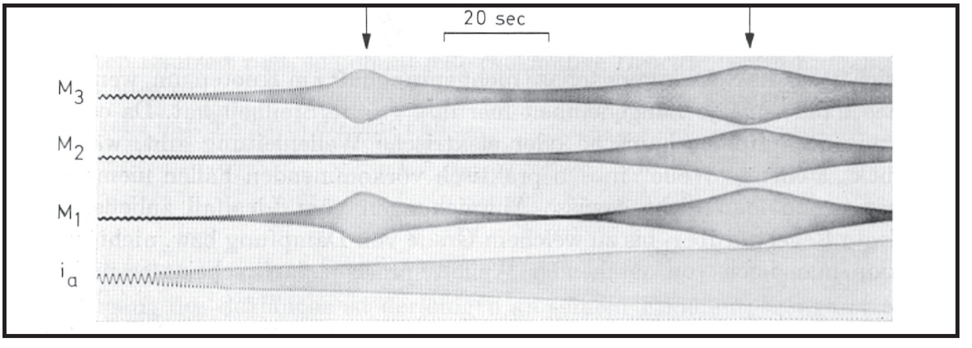

Fig. 4
Resonance of pressure oscillations. From left to right the frequency of the flow-input increases from 0.7 Hz to 6 Hz
Arrows: resonance frequencies at 2.22 Hz and 4.44 Hz i flow,
M pressure (central, middle, end of tube)

In *Fig. 4* only amplitudes can be recognized which vary in a characteristic manner as a function of the frequency.

The importance of calculations in terms of frequency domain can be explained by the fact – as mentioned above – that any signal can be transformed from the time domain into the frequency domain by the so-called Fourier transform. An example in *Fig. 5* (from *Wetterer and Kenner,* p. 258) will be explained below.

The relation which permits to determine the connection between two pulses describes the frequency dependence of the relation between amplitudes and phases, and thence between the pulse contours; it is called transfer function. Recently the transfer function between radial and aortic pressure pulses has been mentioned quite often. This transfer function supposedly permits to calculate the shape of the aortic pressure pulse from the recorded pressure pulses at the radial artery (*6*).

Input impedance and extended analysis of cardiovascular control

The relation between pressure and flow pulses can – in the frequency domain – be described by a transfer function. The amplitude ("modulus") of this function, which depends on the frequency, has the dimension of a resistance. In order to illustrate this function, *Fig. 5* shows the frequency dependence of this function from measurements by O'Rourke and Taylor in a dog (taken from an illustration in *Wetterer and Kenner,* 1968). Dogs have a marked respiratory arrhythmia which is shown as an insert; this simplifies the estimation of the data shown in *Fig. 5.* The function which describes the frequency dependence of the input impedance is characterized by a U-shape with a marked minimum.

In a study published nearly 40 years ago (*2*) it was shown that there are two components of information in the input impedance. The part above the heart rate contains information about the arterial system as discussed above. The second part of lower frequencies, which cannot easily be measured, contains information about cardiovascular control; e.g. baroreceptor reflex and autoregulatory control of blood flow and blood pressure.

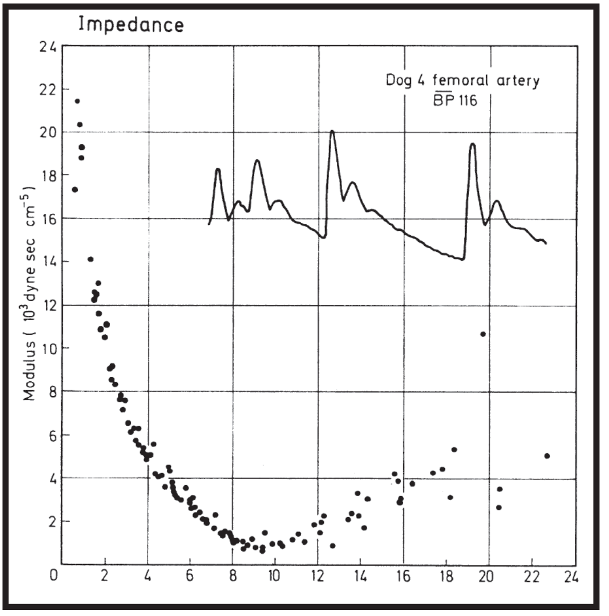

Fig. 5
Input impedance of a dog's aorta
(after O'Rourke and Taylor 1966)

The observation of input impedance in the region of frequencies below the heart rate depends on the presence of slow pressure-, flow-, or heart rate variations. In the example of *Fig. 5* the spontaneous arrhythmia was useful. Also, experimentally generated variations which influence blood pressure and flow like e.g. tilting may be used.

In the paper mentioned (*3*), a simple method for the description and examination of the overall control properties of the circulatory system was derived and discussed. The objective of the study was to present an overlook over the behavior of the whole circulation in response to disturbances in the low frequency region. Therefore, approximated transfer functions were used to describe the circulatory control properties.

The low frequency input impedance (frequency region between about 0.0005 Hz and heart rate) is shown to be a very useful magnitude to examine the closed loop behavior of the system.

The term closed loop condition indicates the presence of feedback within the system. In contrast, an open loop is an experimental condition when the sensors (e.g. baroreceptors) can be stimulated isolated without feedback.

It is found that the basic control mechanisms in local arterial beds as well as in the whole circulation can be described by pressure and flow control loops, both having first-order transfer properties. Considering the circulation as a whole, the fact has to be taken into account that the system, including the heart as an amplifier, is a mechanical feedback system. It is on this system that the autoregulatory and neural (baroreceptor) control loops exert their influence.

A set of equations was established which permits to describe the dynamic properties of the circulatory system under closed loop condition and under a variety of open loop conditions. The effect of blood volume variation, infusion of vasoactive drugs, and the role of a time delay in a control circuit can be demonstrated. The equations in addition yield a simple and powerful stability criterion which permits to predict under which conditions instability and pathologic oscillations of blood pressure, blood flow, and also of respiration may be generated.

Acknowledgement

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