A novel laboratory approach for the demonstration of hemodynamic principles: the arterial blood flow reflection

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Djelić M, Mazić S, Žikić D. A novel laboratory approach for the demonstration of hemodynamic principles: the arterial blood flow reflection. Adv Physiol Educ 37: 321–326, 2013; doi:10.1152/advan.00176.2012.—In the frame of a laboratory training course for medicine students, a new approach for laboratory exercises has been applied to teach the phenomena of circulation. The exercise program included measurements of radial artery blood flow waveform for different age groups using a noninvasive optical sensor. Arterial wave reflection was identified by measurements of blood flow waveforms before and after arterial branching. Students were able to distinguish between different waveforms of blood flow within different age groups. Furthermore, students were given the opportunity to explore the effect of aging on the elasticity of blood vessels. This exercise is an introduction to the fundamental physical laws of hemodynamics that can facilitate the learning and understanding of cardiovascular physiology to students of medicine.

hemodynamics; wave reflection; educational model

Undergraduate students experience considerable difficulties in understanding various physiological processes due to insufficient knowledge of physics, both theoretical and practical. This problem became more evident after the reforms in high school and university education in Serbia that took place at the beginning of this century. In an attempt to approach the physical methodology to students, we developed a new laboratory technique to teach the phenomena of circulation. We introduced noninvasive measurements of arterial blood flow as a part of the laboratory exercise program. The measurements and analyses of the arterial waveform allowed students to understand the phenomena of wave propagation, wave reflection, and backward flow through blood vessels and to identify the influence of aging on the elasticity of blood vessels.

Background. Cardiovascular physiology represents an important part in physiology courses. Laboratory experiments with anesthetized animals are very useful for students to learn and understand some of the basic physical laws and principles. However, these laboratory experiments are rarely practiced at the undergraduate level because of their high cost, the requirement for surgical skills in the laboratory preparation, and ethical issues related to the use of animals (9). Practically, mathematical and physical models can be used to explain many circulatory phenomena. Physical models are useful tools for teaching at the undergraduate level and allow students to perform hands-on experiments (8, 10). They can demonstrate the experimental validity of fundamental physical laws of hemodynamics, such as the equation of continuity, Bernoulli’s equation, and Poiseuille’s law. Application of physical models can significantly help in learning several issues in fluid mechanics relevant to physiology and also enable simple control and manipulation of the experiment. There has been increasing use of computer-based simulations of the complete cardiovascular system in recent years (2, 9). Such simulations, together with mechanical models, can greatly contribute to students achieving better understanding of the complex principles of hemodynamics.

While physicists regularly explain blood flow dynamics through vessels using differential equations, medical students face a considerable challenge dealing with fluid dynamics due to insufficient knowledge of mathematics and physics (11). In our experience, many undergraduate medical students do not adequately understand the phenomenon of wave motion and wave reflections.

Theoretical background. The flow of blood through blood vessels is not continuous; rather, blood propagates as a wave through the arterial tree due to the rhythmic contractions of the heart. The wave motion of blood carries information about the surroundings it passes. On the other hand, the surroundings also influence the waveform through aspects of arterial geometry and the elasticity of vessel walls. Remarkably, blood flow is not solely one way directed. There are several sites along the arterial tree and certain places where wave reflections may occur and cause the blood to move in opposite direction. The reflected wave, superimposed to the original wave, can be easily detected in the blood flow waveform. There is a simple mathematical model that describes this wave phenomenon, based on a half-sine function as an analogy to the pulse wave. From the educational perspective, the use of one-dimensional models could greatly contribute in understanding the propagation of waves, wave reflection, and superposition of waves.

Nowadays, with technology advancement, detection of these wave phenomena in the arteries is achieved by a simple noninvasive measurement technique. The most commonly used techniques are Doppler ultrasound measurements, arterial tonometry, and photoplethysmography. Ultrasound measurements can provide a detailed picture of blood vessels and information about the blood flow through them. Arterial tonometry provides continuous measurements of noninvasive arterial pressure, and photoplethysmography is a simple optical technique able to detect blood volume changes in the microvascular bed of tissue. Application of the photoplethysmography method for measurements of arterial blood flow has steadily increased (1). This optical technique gives information about the continuous changes of hemodynamic parameters that occur over time and therefore can be very helpful to students in understanding and mastering the basic principles of hemody-
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LABORATORY DEMONSTRATION OF ARTERIAL WAVE REFLECTION

It allows plenty of information available to the experimenter, such as:

1. Visualization of the blood flow waveform through the artery
2. Detection of the reflected wave
3. Clear observations of the wave superposition phenomena
4. Identification of the maximum blood flow velocity.

In this article, we present a new laboratory exercise in hemodynamics, designed for medical students at Belgrade University. This experiment was developed at the Department of Biophysics in cooperation with colleagues from the Department of Physiology. The existing physical model of fluid flow used for laboratory practices is not suitable to demonstrate wave reflection, the elasticity of vessels, or backward flow. Therefore, we developed a simple demonstration that allows students to understand these phenomena from the results of direct measurements. Experiments were performed with a noninvasive optical sensor to measure the radial artery (a. radialis) blood flow in participants of different age groups.

**Learning objectives.** The objectives of this laboratory exercise were as follows:

1. To teach students about the basic principles of wave motion of fluid through vessels
2. To teach students how to determine the reflected wave and backward flow in the recorded signal
3. To teach students about the influence of elasticity of vessel to the flow waveform
4. To introduce students to a new method of measuring physiological signals using optical sensors.

**Time required.** This laboratory activity was performed in a single 3-h session.

**Limitations and disadvantages of the exercise.** A laboratory exercise with visualization is generally a good teaching approach to follows theoretical lectures. In this course, laboratory practice were introduced to provide students a better understanding of the biophysical phenomena that occur in arteries. One possibility of achieving visualization of the wave propagation is by recordings of the arterial blood pressure waveform.

There are several sites on the body where the blood pressure waveform can be recorded. The most commonly used sites are above carotid artery in the neck and above the radial artery in the wrist. In these areas, bone and ligaments support the artery, and the artery does not move when external pressure is applied.

The carotid artery pressure waveform is most comparable to the pressure waveform in the ascending aorta and, therefore, presents a preferable site for measurements. The problems that may occur in this recording are related to the difficulties in positioning the sensor above artery, due to the depth in the neck and mobility, and maintaining the sensor in the same position during the measurement. Other problems are related to mechanical stimulation of the carotid baroreceptors that might affect changes in heart rate. An alternative site for wave measurements, to avoid the above difficulties, is the site of the radial artery. Placing the sensor above the radial artery is very easy to perform, and baroreceptor activation does not occur during the recording. The disadvantage of recording at this site is that during the transmission from the proximal artery, the pressure wave is amplified and the pressure waveform is changed. Furthermore, the influence of age, hypertension, and diseases in adults have little effects on the radial artery waveform, whereas these effects can be very well detected in the carotid artery waveform, and, without an applied generalized transfer function, students cannot obtain a real picture of the central aortic pressure waveform from the radial waveform.

The exercise presented in this article is based on measurements of radial artery blood flow. There are several reasons for choosing the radial site instead of the carotid site and also for choosing blood flow waveform recording rather than the blood pressure waveform. In the theoretical part of this exercise, students were taught about fundamental differences in the blood flow and blood pressure waveforms. The practical session, however, was designed in accordance with available experimental equipment. Since our measurement setup did not include the sensor and devices for blood pressure recording but we had the blood flow sensors, we decided to explain the wave phenomena with blood flow waveforms. The lack of certain research components were caused by economy reasons (the economic crises in our country) and a standby in our purchase funds.

Another important reason for choosing the radial site rather than the carotid site, despite the previously mentioned drawbacks, is purely practical. This particular exercise takes place during the freshman year, which includes studies on the radial artery but not the carotid artery. Since, in this semester, students learn the anatomy of the hand, they are able to find the position of the radial artery. The necessity for synchronization between this laboratory exercise and other study subjects led us to choose the site of the radial artery for blood flow recordings. Also, by measuring radial artery flow, we detected differences in blood flow waveforms for different age groups. Following the obtained results (see Fig. 4), we believe that students will be able to better understand Hooke’s law by this study approach.

With the acquiring of the necessary equipment, once the economy recovers, we will be able to redesign this exercise and overcome disadvantages. This laboratory study will be of great benefit to student of medicine to better understand the phenomena of wave propagation through blood vessels.

**METHODS**

The main idea underlying this laboratory exercise was to show students the radial artery blood flow waveform in three age groups: young (age: 20–25 yr), middle aged (age: 40–45 yr), and elderly (age: 60 yr and over).

This exercise consisted of theoretical and experimental parts. In the theoretical part, students had short lectures on topics of wave motion, superposition of waves, Hooke’s law, fluid flow through an elastic tube, wave reflections, and backward flow. The complex mathematical explanations in lectures were reduced as much as possible, and more animated examples were used. A one-dimensional mathematical model of the fluid flow through an elastic tube with a wave reflection at the branching site was fully explained to the students (5, 11). An excellent book, “McDonald’s Blood Flow in Arteries” (5), is recommended for students to better understand hemodynamics instead of books on physics and fluid dynamics.

In the experimental part of the exercise, radial artery blood flow was measured.

**Equipment.** To perform this exercise, the following materials are needed:

1. Photoplethysmographic sensors
2. A data-acquisition board (PCI-20428W, Intelligent Instrumentation)
3. Data-acquisition software (LabView).
The sensor. Blood flow measurements were performed at radial artery of the left arm using the modified photoplethysmographic sensor, as previously described (12, 13). The main parts of the sensor are the infrared (IR) emitter and photodetector. The schematic design of the sensor is shown in Fig. 1. The IR emitter and photodetector were inserted into ECG electrode gel, and the surfaces of all components were in the same plane with the gel surface (Fig. 1).

This configuration was designed to prevent pressure of the sensor parts to the skin. The introduction of an ECG electrode to the system ensured a good contact between the sensor and skin. The sensor was placed at the site where the radial artery closely approaches the surface of the skin, and the arterial pulse was sensed by slight hand pressure. The acquired signal was filtered, amplified, and digitalized in 12-bit resolution (PCI-20428W, data-acquisition board) with a 1-kHz sample rate. LabView software was used for DAQ control and signal monitoring.

Experimental setup. Arterial blood flow measurements were conducted on healthy volunteers (Department personnel, medical and technical staff, technicians, assistants, and professors). Wave reflection was identified with simultaneous measurements of blood flow on two arteries: one at the site before branching and the other at the site after branching (Fig. 2). Two identical sensors were used for this measurement; the first sensor was placed above the radial artery ~2 cm before branching point, and the second sensor was placed above the superficial palmar artery (r. palmaris superficialis) at the point where the pulse was sensed by finger touch ~2 cm after the branching point.

As arterial anatomic variations are frequent, in some people, the superficial palmar artery is near the skin surface and allows blood flow measurements through it (4, 7). The position of the superficial palmar artery in all participants was also verified with ultrasound (ProSound alpha 10, Hitachi Aloka Medical).

Measurements of blood flow in the radial artery were performed in groups containing three age-related volunteers (prearranged and organized before exercise). The first group included assistants, younger technical staff, or nurses. The second group was composed of middle-aged lecturers and staff. The third group consisted of older volunteers who were healthy and without any cardiovascular diseases and problems previously examined by a physician (or senior professors). The blood flow waveform was recorded simultaneously within the same group of volunteers and between the different groups, thus enabling
students to identify similarities and differences in the signals. During the measurements, the blood flow waveform was monitored on PC displays.

RESULTS AND DISCUSSION

Expected results. Before the theoretical part of the exercise, the wave reflection phenomenon was demonstrated to students. Students were provided with printed graphs of measured blood flow waveforms before and after arterial branching (Fig. 3). During the following learning session, students discussed the appearance of a negative peak on the graph of the blood flow waveform in the artery before branching (Fig. 3, bottom graph, arrow).

When asked about the reason for the appearance of such a peak before arterial branching and not afterward, none of the students was able to answer correctly. In the next step, students attended the theoretical lecture, after which the previous question (Fig. 3) was brought up again as the subject of discussion. This time, most of the students concluded that the negative peak corresponds to the backward flow induced by wave reflection due to the arterial branching (3, 5, 6). Their conclusion was based on the example of the reflection of waves, superposition of waves, and mathematical model of fluid flow that were explained in the theoretical part of the exercise (see the APPENDIX).

In the next session, groups of examinees measured blood flow waveforms. Upon completion of the measurements, students were provided with a printed graph of the blood flow waveform for one cardiac cycle of each volunteer (Fig. 4). Graphs were divided into age groups to facilitate the identification of similarities. The following topics were set for discussion:

1. Similarities and differences of blood flow waveforms by age group.

2. The main cause of increased wave reflections with age. Nearly all of the students found that subjects of the same age group had similar blood flow waveforms of one cardiac cycle. In addition, they were able to notice a clear difference in waveforms between age groups and found that the amplitude of the negative peak increased with an increase in age (Fig. 4, arrows). Referring to the first demonstration of wave reflection, students concluded that it was the backward flow of the reflected wave due to arterial branching, i.e., the reflection coefficient increased with age. A few students explained the

Fig. 4. Recorded radial artery blood flow signals of young (top), middle-aged (middle), and elderly (bottom) subjects for one cardiac circle. Arrows indicate the differences in waveforms between the age groups.
phenomenon by referring to Hooke’s law and examples of fluid flow through an elastic tube from the theoretical part of the exercise and came to the conclusion that the elasticity of the arteries decreases with age (3, 5, 6).

Evaluation of student work. The exercise presented here has been practiced for the last 2 yr as a part of the Introduction to Hemodynamics elective course of the Department of Biophysics. Responses of students who attended the course (students of the first-year program) were very positive. Students described the demonstration as a new and different way to explain the laws of fluid dynamics. Anonymous surveys were conducted among second-year students after completion of the course of medical physiology. According to the results of the surveys, students who attended this elective course, easily, in a relatively short time, mastered the subject of cardiovascular physiology. Although for profound understanding of physical essentials substantially more lectures are needed, these exercises were shown to be of great help to students in comprehending the complex phenomena of hemodynamic processes.

Final remarks. The exercises described here were designed as educative tools intended to stimulate students to develop better skills for understanding the basic physical rules in wave propagation of fluid through vessels. These exercises enabled students to approach the phenomena of the circulatory system, either normal or pathological, with more success. In addition, the proposed exercise demonstrated, in an indirect way, the physiological changes that occur with aging. Furthermore, these exercises enabled students to apply physical laws and principles in different physiological processes and recognize the phenomena of wave motion.

For the first time, students were introduced to time-dependent physiological signals and had the opportunity to personally participate in experimental measurements. Students also learned about the new noninvasive method of measuring physiological signals. The chance to measure their own arterial blood flow attracted great attention and motivation for the exercise among students.

This knowledge will be certainly valuable for students in advanced educational levels and, later, in their clinical and research activities (e.g., dicrotic notch, terminal resistance, flow in the stenotic vessel, etc.). Further upgrades of the exercise include additional explanations of the continuity equation, Bernoulli’s equation, and Poiseuille’s law, which should grant students better insights into the physics of pulsatile flow.

APPENDIX: THE MATHEMATICAL MODEL OF WAVE REFLECTION

Discontinuity in the elastic properties of blood vessels along the arterial tree can occur due to changes in arterial diameter or bifurcation. Wave reflection can occur at any point where arterial properties change. The possible reflection sites are branching points. The behavior of blood before and after arterial branching can be simulated as a one-dimensional incompressible flow in an elastic tube (5, 11). An incident flow wave \( Q_i \) traveling from the origin can be represented by the following equation:

\[
Q_i = Q_0 \sin(\omega t - kx)
\]

where \( Q_0 \) is wave amplitude, \( \omega \) is angular frequency, \( t \) is time, \( k \) is wave number, and \( x \) is distance from the branching point.

If there is no reflection, the arteries are well matched and the sum of flow through the daughter segments is equal to the flow through the parent segment (Fig. 5); this is described by the following equation:

\[
Q_i = Q_1 + Q_2
\]

If a reflection occurs, then the reflected wave \( Q_r \) travels backward toward the origin (Fig. 5, dashed line), which can be represented by the following equation:

\[
Q_r = \Gamma \times Q_0 \sin(\omega t + kx)
\]

where \( \Gamma \) is the reflection coefficient and describes either the intensity or amplitude of the reflected wave relative to the incident wave.

The total flow at distance \( x \) from the branching point will be the superposition of incident and reflected waves, as described by the following equation:

\[
Q = Q_i - Q_r = Q_0 \sin(\omega t - kx) - \Gamma \times Q_0 \sin(\omega t + kx)
\]

The reflected wave has a negative sign, since it moves in the opposite direction of the incidental wave. Figure 6 shows an example of the new wave formed as the sum of two waves.

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AUTHOR CONTRIBUTIONS
Author contributions: M.D. and S.M. performed experiments; S.M. and D.Z. interpreted results of experiments; D.Z. conception and design of research; D.Z. analyzed data; D.Z. prepared figures; D.Z. drafted manuscript; D.Z. edited and revised manuscript; D.Z. approved final version of manuscript.

REFERENCES