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The history of blood pressure measurement: from Hales to our days

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Abstract

This article reviews the history of blood pressure (BP) measurement by invasive and noninvasive methods. It also discusses the idea of considering arterial hypertension as independent disease. The common information for arterial BP levels in different division of vascular bed is described.

Key words: arterial blood pressure, invasive and noninvasive methods of registration, arterial hypertension

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История измерения артериального давления: от Хейлса до наших дней

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Резюме

В статье анализируются литературные данные об истории измерения артериального давления (АД) инвазивным и неинвазивным методами и возникновении представлений об артериальной гипертензии как самостоятельном заболевании. Приводятся общие сведения о величинах АД в разных отделах артериального сосудистого русла.

Ключевые слова: артериальное давление, инвазивные и неинвазивные методы регистрации, артериальная гипертензия

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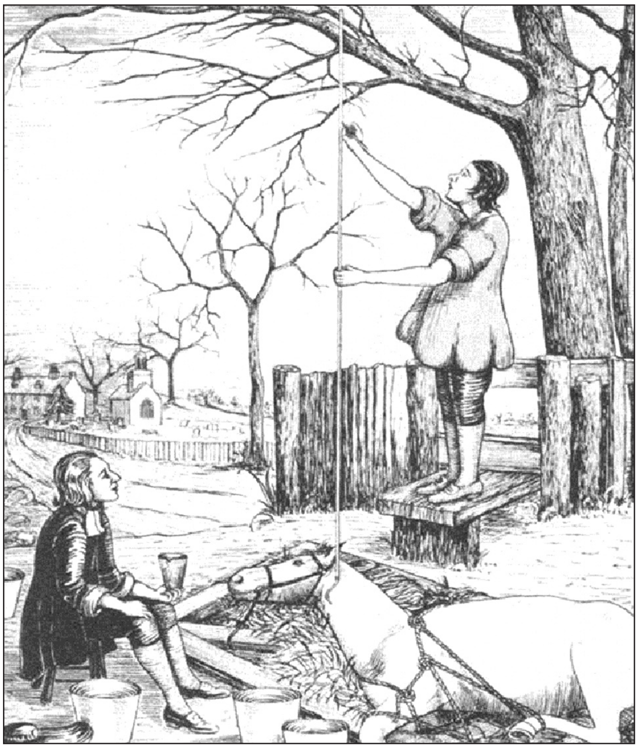
Introduction

Blood pressure (BP) as a physiological constant is determined by peripheral vascular resistance and cardiac output. If blood rheological properties are not considered, peripheral vascular resistance is determined by regional vasopressor reflexes from tissue receptors and local vasodilation humoral mechanisms mediated by tissue metabolism. The cardiac output also depends on oxygen demand (and, ultimately, on the rate of tissue metabolism). Consequently, "normal BP value" is a function of the metabolic rate of the entire body.

BP is a rather fast-moving constant and is not maintained at the strictly defined level. When it comes to the change of sleep and wake, rest and physical activity (i. e. depending on the general activity), BP adapts to a new level. In this respect, every organ can be supplied with the required blood flow at any pressure level, if the latter is in accordance with arteriolar resistance [1].

BP as a measure of the circulatory system was mentioned in the Middle Ages by G. Harveo (1628). In his famous work, a translation of which was published in 1948 [2], Harveo wrote: "There is one error, against which the surgeons should be warned. In case of amputations, resections of sarcomas, injuries, the blood leaves the arteries and jets out". Although Harveo did not use the concept of BP, it is unmistakable that he understood what this "jet" was.

Figure 1. Hale's experiments to determine blood pressure of a horse (Booth J., 1977)



The first direct BP measurement (direct manometry) was carried out in 1733 in a horse by philosopher and inventor Stephen Hales [3–5]. The researcher inserted into the left femoral artery of the animal a brass pipe that was connected with a vertical glass pipe (Fig. 1). After untying the ligature of the artery, the height of a blood column in the glass pipe reached 8–9 feet, also fluctuations of the height were seen synchronous with heartbeats. Further research carried out by T. Young showed that "blood pressure at the beginning of the main aortic stem remains the same without decrease in lower branches" [6]. T. Young examined BP values in dogs in various points of the vascular system down to arteries 200 μm in diameter.

In 1828, French researcher J.L.M. Poiseuille was awarded a gold medal by the French Royal Academy of Medicine for his doctoral thesis on the use of the U-shaped mercury manometer for BP measurement [7]. To prevent blood coagulation, the author used soda solution. BP was started to be measured in millimeters of mercury column, and also pressure of 1 mmHg/cm^2 was started to be denoted as "torr" in honor of Evangelista Torricelli. In the absolute system of units, the unit of pressure is defined as action of the force unit (one dyne) on the surface of one squared centimeter. This unit is called "bar". One torr equals 1333 bars or dyn/cm^2 J. L. Poiseuille found that BP measurement with the manometer invented by him gave the value of 159 torrs in a horse and 151 torrs in a dog [8].

The developments of J. L. Poiseuille were continued by professor of comparative anatomy K. Ludwig who in 1847 invented a kymograph [9]. In fact, a graphic method of recording physiological data was found. The experiments of J. L. Poiseuille continued, but the procedure was improved — the cannula that was inserted into the artery of an animal and the mercury manometer remained the same, but a float with a writing pen attached was buoyed up by the mercury column and all changes in BP were recorded on the kymograph trace.

The first estimation of the BP in man was made by surgeon Faivre during an intervention of femoral amputation in 1856. The author connected a mercury manometer to the artery and thus obtained direct pressure recording. He found the BP (mean) in the femoral artery to be 120 mmHg (or 120 torrs), and in the brachial artery — between 115 and 120 mmHg.

The direct method of BP measurement underwent no substantial changes up to the present moment. A needle or cannula that is connected through a pipe to manometers of various modifications (mercury, strain-gauge, inductive, capacitance) is inserted directly into the artery. The main areas of use are physiology and cardiac surgery. Direct manometry is virtually the only method of pressure measurement in cardiac cavities and central vessels. Venous BP can also be reliably measured using the direct method.

In clinical and physiological experiments, invasive daily BP monitoring is used. A needle inserted in the artery is flushed with heparinized saline solution through a microinfusor, and the signal of the pressure sensor is recorded continuously. Instead of a needle, teflon or polyurethane arterial lines or cannulas can be used. Changes in intravascular pressure are transmitted via a liquid-filled connecting pipe to the membrane of the pressure sensor where mechanical vibrations are converted into an electrical signal proportional to pressure fluctuations. Several types of sensors-transducers can be used: strain-gauge, capacitance, inductive. The signal is amplified and filtered to remove high-frequency interference. Pressure curve is seen on the display where graphic and digital information is represented. Frequency characteristics of the monitoring system that should have the frequency of 5 to 20 Hz to enable the accurate signal display are of great importance.

The need for long-term BP recording in animals under the conditions close to natural behavior and without contacting the researcher as well as the development of technical equipment arose a question of telemetry recording methods of biological processes and, in particular, BP in experimental practice. This idea appeared in 1984 in the laboratory headed by professor F. Halberg in the University of Minnesota. The suggestion was to implant in the body of an animal small sensors generating a radiosignal and transmitting it onto a special receiver. In 1985, a sensor was developed for monitoring of body temperature, electrocardiogram and motor activity in rats. In 1988, the first sensor for BP monitoring appeared. The pressure sensor that is usually placed into the abdominal cavity of an animal consists of an electronic module put in a housing, and a catheter going out of it. The catheter inserted into the aorta is filled with incompressible liquid through which the pressure is transmitted to the sensing element located in the housing of the transmitter. Sensor power supply source is a galvanic element. Continuous work time of one sensor is 1.5 to 12 months depending on its modification. The receiver of the signal generated by the pressure sensor is connected to the data collection unit with a cable. Modern programs developed specially for telemetry monitoring enable simultaneous continuous BP in several animals.

Invasive catheter insertion into the lumen of a vessel is required for direct BP measurements. Therefore, along with direct methods of BP measurement, non-invasive techniques began to develop. First studies were carried out in 1855 by K. Vierordt. The researcher postulated that non-invasive technique (sphygmography) might be used to measure the amount of external pressure needed to stop the pulsation in an artery. The author tried to put his suggestions into practice but failed. The sphygmograph of K. Vierordt was modified by J. E. Marey in 1860. J. E. Marey improved the method of graphic recording of arterial pressure pulses. Moreover, he also increased the accuracy of pressure recording. Using the same principles of external pressure measurement, he enclosed the patient's arm in a glass chamber filled with water (in fact, in a plethysmograph) connected to a sphygmomanometer, and radial artery pulsations were recorded on a kymograph. The pressure in the chamber was recorded by a mercury manometer [8], and this pressure, when arterial pulsations ceased, was registered as systolic. In the mercury manometer, there was a float with a writing pen for recording pressure changes in the plethysmograph on a smoked trace of the kymograph. When the pressure in the glass chamber reached the value corresponding to the minimum BP, oscillation amplitude increased and continued to increase. At so called average dynamic pressure, the oscillations reached their maximum level. Then they began to decrease gradually down to the moment corresponding to the systolic pressure level. J. E. Marey's method required sophisticated and fragile equipment, but it still turned out to be promising since it allowed measuring the average dynamic pressure level.

The invention of J. E. Marey was widespread in medicine. In England, these studies were continued by R. E. Dudgeon and J. S. Burdon-Sanderson. The accuracy of systolic pressure measurement were shown to depend not only on its level but also on the vascular wall resistance.

Marey's oscillometric method is developed nowadays as well. In 1976, Criticon company developed and brought to the market the first bedside automatic equipment for BP measurement based on the modified oscillometric method. The pressure in the occlusive cuff reduces step-by-step, 6–8 mmHg per step, and at each pressure level, the amplitude of pressure micropulsations in the cuff is analyzed, that arise due to the transmission of the artery pulsation to the cuff. Since 1980-s this method has been used in bedside and portable daily BP monitors as well as in devices for BP self-control.

An Austrian doctor S. S.K. R. von Basch in 1881 finally ave the opportunity to stop artery puncture for BP recording. Based on the principles of K. Vierordt, at the site of artery pulsation von Basch placed an inflatable rubber reservoir filled with water that put pressure on the artery until pulsations ceased. The reservoir was connected to a mercury manometer, and the cease of artery pulsation occurred at the external pressure corresponding to the systolic arterial pressure. To check the accuracy of measurements, I. Zadek simultaneously recorded BP in the carotid artery invasively and using the von Basch device in dogs. The results obtained by different methods agreed with each other. Later, both authors stated that, in patients with atherosclerosis, BP was higher, and in patients with fever it was lower than in healthy subjects.

In 1896, S. Riva-Rocci published the description of a method of BP measurement that is relevant till nowadays [3]. The device was easy-to-use and safe for the patient. In fact, it looked quite the same as modern tonometers — like a hollow rubber bag placed into a cuff of inextensible material that was wrapped around the upper arm and inflated with a rubber bulb. The pressure in the cuff recorded by the mercury manometer increased until the pulsation stopped. After the pressure was slightly released, the mercury level in the manometer fell, and the level at which the pulsation reappeared corresponded to the systolic pressure. The only disadvantage of the device was its too narrow cuff (5 cm) that formed the areas of increased pressure; therefore, the readings were slightly overestimated. In 1901, this mistake was corrected by von Recklinghausen who widened the cuff to 12 cm.

In 1899, G. Gartner created the next generation of devices for non-invasive BP measurement and called it tonometer.

Along with all the advantages of the above-named non-invasive methods, they all had one limitation — they could be used to measure the systolic BP only. The level of the systolic BP was determined by palpating the artery. Sound, or auscultatory, method of BP measurement was discovered in 1905 by Nikolai Sergeevich Korotkoff, a surgeon from St Petersburg. While providing aid to the wounded during the Russo-Japanese war, N. S. Korotkoff was faced with great difficulties of surgical treatment of posttraumatic aneurysms. The young doctor set a goal to find the symptoms that would help a surgeon predict the future of a limb even before the ligation of the injured artery; he began to auscultate an arterial aneurysm after the placement of the Riva-Rocci cuff and found that if the external pressure was applied to the artery, sounds (tones, murmurs) arose in it, that ceased as soon as the external pressure exceeded the systolic pressure. N. S. Korotkoff also noted that if the stethoscope was placed over the brachial artery at the cubital fossa distal to the Riva-Rocci cuff, sounds could be heard when the artery was occluded or the blood flow in the artery restored. N. S. Korotkoff wrote a brief article only 207 words long about the principles of the BP recording method he discovered [10] and on November 8, 1905 presented the sound method of non-invasive BP measurement in the Military Medical Academy. Professor M. V. Yanovsky contributed to the improvement of the method. In 1912, D. O. Krylov, a student of M. V. Yanovsky, made a report on the 4th Congress of Russian Therapists where various aspects of the Korotkoff's sound phenomena were summarized. In 1962, the World Health Organization recommended the method of N. S. Korotkoff as the most reasonable for medical practice.

The theory explaining the main characteristics of Korotkoff's sounds is based on the idea that sound is generated by periodic passage of the pulse wave front under the cuff, that became steep due to non-linear expansibility of the occluded artery, tissue elasticity, interaction between the pulse wave and the reflected wave. These murmurs could also be due to the blood flow turbulence. Manometer reading by ear is also carried out with a certain error depending on researcher's personal characteristics — reaction time, skillfulness, etc. Own frequency of brachial soft tissues falls within the range of approximately 140 Hz, and the tissues do not have any considerable effect on the artery pulsation transmission to the cuff. In summary, the tonometer inaccuracy has three components: the method itself, manometer accuracy, and error of estimation of the moment of reading. The readings are also influenced by the rate of air pumping into the cuff, rate of release and the level of pressure created in the cuff. BP values measured according to Korotkoff are believed to exceed the true values of the systolic pressure by 7–10 %, and of diastolic pressure — by 28 % [11].

In 1935, N. N. Savitsky together with the colleagues from the Leningrad Institute of Fine Mechanics and Optics developed a new type of a sensitive optical differential pressure gauge that allowed improving the oscillometric method of BP measurement with a cuff in human subjects. The method is based on the use of a differential pressure gauge with a common membrane between two chambers, the pressure from the cuff being transmitted to one of the chambers. N. N. Savitsky developed in detail and gave scientific credence to an absolutely new method of oscillogram reading. The differential oscillogram received with the help of the developed device was called a tachooscillogram (tachus — fast, quick; oscillum — swinging, vibration; gramma — recording) to emphasize that it was the first time derivative of the volume. Tachooscillographic method of blood pressure measurement differs from other oscillographic methods: it does not register the changes in the vessel volume under the cuff but the rate of these volumetric changes is optically recorded. Besides, the optical recording considerably exceeds in sensitivity other available devices.

As measuring devices for BP recording, the following are used currently: devices that mechanically perceive and mechanically display or record the movement; devices that mechanically perceive and optically record; devices that transform mechanical motions into electrical pulses and display them [12].

In the clinical practice, along with invasive BP monitoring, methods of long-term non-invasive recording are used. Its inventor N. Holter, in 1961, suggested continuous recording of the electrocardiogram (during 24 hours) with a portable device — recorder. The obtained results allow to find cause and effect relationships between changes in the cardiogram and behavioral activity of the person during monitoring. Later, apart from the electrocardiosignal, methods of long-term BP recording were also developed.

Daily BP monitoring allows control of BP during a day or several days. For BP recording, a cuff is put on the patient's upper arm and connected to the recorder with a hollow pipe. A small device (compressor) at set time intervals pumps the air into the cuff and then releases it. In the daytime, the measurements are usually carried out every 15 minutes, at night — every 30 minutes. A sensitive sensor determines the time of appearing and ceasing of the pulse waves (as during the normal measurement according to Korotkoff). The readings are recorded and kept in the memory. They are read with a computer program and then the results are analyzed.

Today, novel diagnostic systems can cause a real revolution in cardiology, i. e. provide the practitioners with the possibility to carry out highly-accurate daily BP and pulse wave monitoring, and the patients — with the possibility to maintain their ordinary lifestyles. The approach is based on the applanation tonometry that was for the first time used in ophthalmology to measure intraocular pressure. For BP recording, a high-sensitive sensor (that can be in a shape of a watch) is securely fixed in the projection of the radial artery. The use of software and appropriate equipment enables detailed pulse wave analysis that allows to record such pulse pressure values as pulse wave (arterial wall vibrations from the heart to resistance vessels) and reflected wave (arterial wall vibrations from resistance vessels to the heart), and to calculate the values of central aortic pressure by computer processing.

Currently, there are methods of non-invasive BP recording in experiment. The most frequently used in rodents electroplethysmographic BP measurement in the caudal artery ("*tail-cuff*") is based on the same principle as BP measurement in human according to Riva-Rocci. The lumen of a large artery is occluded with a cuff and, during the reduction of the air pressure in the cuff, the pressure level is recorded at which the blood flow through the occluded area restarts. The value corresponds to the systolic BP and the method allows repeated BP measurements in long-term chronic experiments.

Along with all the advantages, all the non-invasive BP measurement have one common problem — they provide discrete BP recording at certain intervals. A number of novel approaches allow BP detection nearly at every heartbeat.

In 1963, G. L. Pressman and P. M. Newgard suggested a continuous method of BP recording (tonometric method) based on partial squeezing of limb arteries and recording of the lateral pressure using strain-gauge sensing elements installed into the occlusive bracelet. In 1969, J. Penaz suggested the method that is called "volume clamp" in English-language literature. The method is based on the continuous assessment of the volume of finger arteries using photoplethysmography. For BP recording, an electro-pneumatic control system is used. It creates counter pressure in the cuff around the finger, that counteracts the distension of arterial vessels lying under the cuff. If the diameter of finger arteries is constant, the distending pressure in the arteries is kept constantly close to zero, and the pressure in the cuff begins to "repeat" the BP in finger arteries. Both stationary (Finapres) and portable versions (Portapres I и II) are used in the clinical practice. However, diastolic BP measured with these devices depends on the state of finger arteries and, as a rule, is lower than in the brachial artery.

Currently, the main values being measured are systolic or maximum, diastolic or minimum, pulse and average, or average dynamic, BP. N. N. Savitsky [12] also distinguished piezometric (lateral) pressure.

Anywhere in the vascular system the blood pressure depends on:

a) atmospheric pressure;

b) hydrostatic pressure pgh determined by the weight of the blood column with height h and density p;

c) pressure provided by the pumping function of the heart.

BP is maintained at approximately the same level whether in humans or in other warm-blooded animals regardless of their size — horses, dogs, cats, rabbits, mice. In cold-blooded animals it is approximately 10 times lower. On the other hand, BP in giraffes is almost twice as large as in other mammals — approximately 315 versus 240 mmHg [13].

The appropriate BP value is necessary for the propulsion of the certain blood volume per unit time through the capillary system. Between the heart and the capillary vessels, main and organ arteries and arterioles are located.

Pressure distribution in various vascular regions was most thoroughly analyzed by A. A. Bogomolets [14]. If the aortic pressure is approximately 130 mmHg, the BP in small auricular arteries in a rabbit when heated is 68 mmHg. The maximum resistance to blood flow is provided by arteries ca. 0.12 mm in diameter, and the pressure reaches its maximum in the precapillary system [15].

The difference in pressure on the inner (P_i) and outer (P_o) vessel walls is called transmural pressure (P_t), $P_t = P_i — P_o$. The transmural pressure is an essential characteristic of the circulatory system that determines the heart load, peripheral blood stream and a number of other physiological parameters.

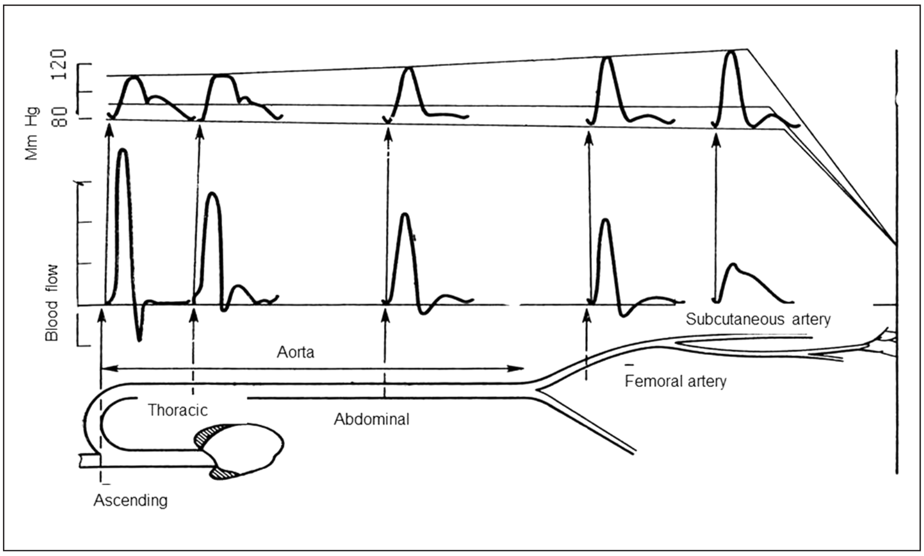
The transmural pressure does not cause blood movement from one point of the vascular system to another. For example, the time-average transmural pressure in a large arm artery makes ca. 100 mmHg (1.33 10^4 Pa). At the same time, blood movement from the ascending aorta to this artery is caused by the difference in transmural pressures between the mentioned vessels, that makes 2–3 mmHg (0.03 10^4 Pa).

During movement of the pressure wave through the arteries, their walls expand due to deformation, forming a pulse wave. This deformation at each vessel portion is determined by the vascular wall rigidity and the level of the transmural BP. Pulse curve is a curve characterizing the deformation of the vascular wall in this vessel part, that occurs under the influence of the variable BP.

The state of the arterial wall has a substantial impact on the pulse wave transit. The more distensible the vascular wall is and the higher blood viscosity is, the slower the pulse wave is transmitted and the sooner it fades. Narrowing of arteries and arterial tree branching also contribute to the weakening of the pulse wave. Pulse wave reflection takes place in various parts of the vascular bed. Precapillary vessel resistance acts as a "blind end" for the pulse wave [15].

Pulse wave reflection gives a reason for different levels of the systolic BP in the aorta and main vessels. The site of measurement has a significant impact on the BP value. The shape of the BP pulse wave changes with pulse wave movement from the centre (proximal portion of the aorta) to the periphery (Fig. 2). At the high pressure wave velocity (in case of reduced arterial wall distensibility), reflected waves return earlier than usual and overlap with the systolic portion of the BP curve. Upon that, with movement of the pulse wave distally from the aorta, the systolic BP gradually increases, and the diastolic BP gradually decreases [16]. If vasodilating agents are used, this difference increases. Since the radial artery is located more distal, the systolic BP there is usually higher than in the aorta. The systolic component of pulse pressure may increase by 15–20 mmHg upon movement of the pressure wave in the distal

Figure 2. Mean and pulse pressure change along the arterial tree (Folkov D., Nell E., 1976)



Note: from the top down — pressure, blood flow, arterial tree.

direction [17]. The average BP level remains relatively constant. Therefore, the average BP can be used as a measure of the central (aortic) pressure.

According to the anatomical and physiological structure of the cardiovascular system, a distinction is made between intracardial, arterial, venous and capillary BP.

During ventricular emptying, the systolic BP is recorded, that in grown-ups makes normally 100–140 mmHg; at the end of the diastole, the diastolic BP is measured, that makes 70–80 mmHg. BP levels in children increase with age and depend on multiple endogenous and exogenous factors. In newborn babies the systolic BP is 70 mmHg, and then it increases up to 80–90 mmHg.

The increase of the systolic BP above 140 mmHg and of the diastolic BP above 90 mmHg is called arterial hypertension.

The studies of R. Bright that started in 1827 and were described in 1836 should be considered as the beginning of arterial hypertension understanding as an independent disease [18]. The author linked chronic renal diseases with the changes in the cardiovascular system that manifested as a diastolic shock on the aorta and left ventricular hypertrophy [19]. R. Bright had no way of measuring BP, so his conclusions were based only on pulse palpation on the radial artery. In 1872, W. W. Gull and Y. G. Sutton [20] postulated that the Bright disease was caused by generalized "hyaline fibrinoid" of arteries and capillaries, and that these vascular changes caused myocardial hypertrophy and renal scarring.

In 1852, G. Johnson found smooth muscle hypertrophy of renal afferent arterioles, that he interpreted as a smooth muscle response to the increased intravascular pressure. L. Traube in 1856 came to a conclusion that the increase of the left ventricular diameters found in a number of patients was caused by "high arterial tension". Lastly, in 1874, F. A. Mahomed [21] using a sphygmomanometer measured the BP clinically and made an assumption that diseases of arterioles accompanying the Bright disease might be caused by an increase in BP. Next year K. Potain made an assumption that the increase of the left ventricular diameters in a number of patients was also caused by an increased BP. In 1876, Gowers using ophthalmoscopy described retinal arteriolar constriction in patients with high BP. Later, in 1889, H. Huchard paid attention to the fact that BP increase was not only found in the case of degenerative changes in the kidneys, but frequently preceded them. Lastly, in 1896, T. Albutt showed that increased BP could be observed without renal pathology and in elderly people. He called this condition "senile plethora" ("hypervolemia of the elderly") [21]. In 1911, E. Frank introduced the term "essential hypertension" into the medical practice to describe hypertension of unknown origin. In 1922, G. F. Lang suggested to call the

BP increase “hypertensive disease” when no association of organ damage with other diseases was found. According to the decision of the World Health Organization made in 1978, the terms “essential hypertension” and “hypertensive disease” are considered as synonyms.

Conflict of interest

The authors declare no conflict of interest.

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