**REVIEW**

# History of Blood Pressure Measurement in Newborns and Infants

**Kamil JAVORKA**[1]

[1]Department of Physiology, Comenius University in Bratislava, Jessenius Faculty of Medicine, Martin, Slovak Republic

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**Summary**

The development of methods for measuring blood pressure (BP) in newborns and small children has a rich history. Methods for BP measuring in adults had to be adapted to this age group. For measuring BP in direct invasive way, a suitable approach had to be found to access the arterial circulation through the umbilical and later radialis artery. Currently, results obtained from direct invasive BP measurement are considered the "gold standard". The development of non-invasive methods for BP measuring in newborns and children began with the use of von Basch's sphygmomanometer (1880). In 1899, Gustav Gärtner constructed the device, which was the basis for the flush method. After the discovery of the palpation and auscultation methods, these methods were also used for BP measurement in newborns and children, however, the BP values obtained in these ways were typically underestimated using excessively wide cuffs. From the auscultation method, methods utilizing ultrasound and infrasound to detect arterial wall movement and blood flow were later developed. The oscillometric method for BP measurement was introduced by E. J. Marey so early as in 1876. In 1912, P. Balard used the oscillometric technique to measure blood pressure in a large group of newborns. Through different types of oscillometers using various methods for detecting vascular oscillations (such as xylol method, impedance and volume plethysmography, etc.), the development has continued to assessment of vascular oscillations by modern sensor technology and software. For continuous non-invasive blood pressure measurement, the volume-clamp method, first described by Jan Peňáz in 1968, was developed. After modification for use in newborns, application of the cuff to the wrist instead of the finger, it is primarily used in clinical physiological studies to evaluate beat-to-beat BP and heart rate pressure variability, such as in the determination of the baroreflex sensitivity.

**Key words**

History • Blood pressure measurement • Invasive • Non-invasive methods • Newborns • Oscillometry • Continuous blood pressure monitoring

**Corresponding author**

K. Javorka, Department of Physiology, Jessenius Faculty of Medicine, Comenius University, Malá Hora 4C, 036 01 Martin, Slovak Republic. E-mail: kamil.javorka@uniba.sk

## Introduction

Monitoring blood pressure (BP) has become a routine practice in all age groups, including newborns. The development of BP measurement methods has progressed from invasive to non-invasive, from animal studies to human studies, and from adults to children and newborns.

The history of medicine lacks a comprehensive description of the development of blood pressure measurement methods in newborns and young children, in whom, for different reasons, conventional methods applicable to adult humans could not be applied. The aim of this paper is to present an overview of this history.

## Development of methods for invasive blood pressure measurement

It is interesting that since the description of the blood circulation by W. Harvey (1628), more than 100 years have passed since blood pressure was first measured.

The first BP measurement was made by

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an invasive method in animals. Stephen Hales published the results of blood pressure measurements in animals in his work “Haemastatics” (1733), which appeared in the second volume of Statical Essays [1]. Up to more than 120 years has it been managed to measure BP in humans. Blood pressure in adult patients was measured invasively by the surgeon Faivre [2] in Lyon in 1856.

In 1929, Haselhorst [3] measured blood pressure in newborns by inserting a needle into the umbilical vein during a cesarean section in three term infants still in utero. The average pressure was 25 mm Hg. These experiments were mainly designed to determine the appropriate time to cut the umbilical cord and to ascertain the size of the placental transfusion.

In 1938, Woodbury *et al.* [4] inserted a needle into the umbilical artery shortly after birth in 37 newborns. Spontaneous closure of the umbilical vessels was delayed by immersing the body in warm water. They used a Hamilton´s manometer with pressure transmission to a silvered membrane, the deformation of which reflected light beams onto photographic film. In full-term newborns, they determined BP systolic as 80.1±8.1 mm Hg and diastolic BP 46.3±8.2 mm Hg. In preterm infants, the pressure was lower and correlated with gestational age. This study is considered groundbreaking, as previous attempts to measure blood pressure invasively were limited by the use of inappropriate manometers and should not be taken into consideration [5].

In the 1950s and 1960s, the development of suitable catheters, low dead-space transducers, sensors, particularly strain gauge type and electromanometers, took place. These technological developments enabled the further development of the method of direct measurement of neonatal blood pressure. Wallgren *et al.* [6] simultaneously recorded blood pressure using a catheter inserted into the umbilical artery together with intraesophageal pressure in the first few minutes after birth. Other authors, such as Rudolph *et al.* [7], began using invasive methods to measure BP in pathological newborns with respiratory distress syndrome (RDS).

In 1975, Todres *et al.* [8] tried percutaneous catheterization of the a. radialis in critically ill newborns. As today's practice has shown, their observation of the possibility of monitoring blood pressure also by this way was correct.

For ethical and practical reasons, non-invasive methods of blood pressure measurement began to be developed at the same time, used first in adults, later in children and newborns.

## Development of methods for non-invasive blood pressure measurement

*Mechanical sphygmomanometry*

The first non-invasive methods for the assessment of cardiovascular function were focused on the evaluation of the quantity and quality of arterial pulse with sphygmometers and sphygmographs.

Jules Herisson [9] constructed one such apparatus in 1833. His sphygmometer was composed of graduated glass tube terminating in a semi-globular steel ball closed by a membrane (Fig. 1a). The mercury reservoir was pressed manually against the wrist above the a. radialis until the oscillations of the mercury column were visible. This allows the pulse to be studied in terms of its strength, regularity and rhythm. Herisson described the relationship between the accentuated pulse, left ventricular hypertrophy, and apoplexy, but he did not measure blood pressure.

In 1855, Karl von Vierordt [10] formulated the principle that “the blood pressure in a vessel can be determined by the external counterpressure necessary to stop the pulsation in the artery”. Based on this still valid principle, he constructed a complicated mechanical device and was the first to attempt to measure blood pressure in a non-invasive way. He determined the arterial BP value in the radial artery. The counterpressure was estimated using weights placed on the lever bowls of the sphygmomanometer connected for recording to the kymograph (Fig. 1b).

Another researcher who was looking for the possibility of non-invasive blood pressure measurement was Samuel Siegfried Karl Ritter von Basch. In 1880, he constructed an apparatus [11] similar to the Herisson's sphygmometer (Fig. 2a). The BP was measured by applying the pressure until the pulse disappeared in the radial or temporal artery. For portability and practical clinical use, von Basch replaced the mercury manometer with an aneroid manometer (Fig. 2b). In the days of mechanistic sphygmomanometry, the diastolic pressure was not determined; only one pressure value, considered the highest (systolic) pressure, or mean blood pressure, was measured.

*The first BP measurements in children and newborns*

Karl von Vierordt in his monograph “Physiologie des Kinderalters”, published in 1881 [10], discussed possible differences in blood pressure values during ontogenesis. Using data from other authors, such

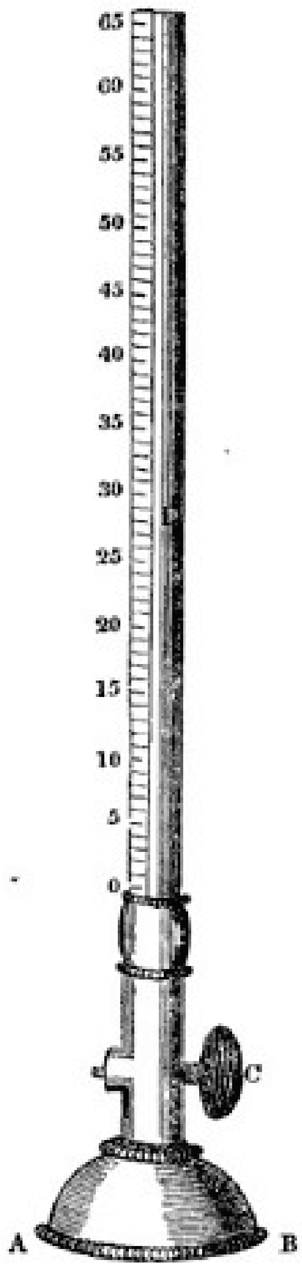

Fig. 1a. Herisson's sphygmometer [9].

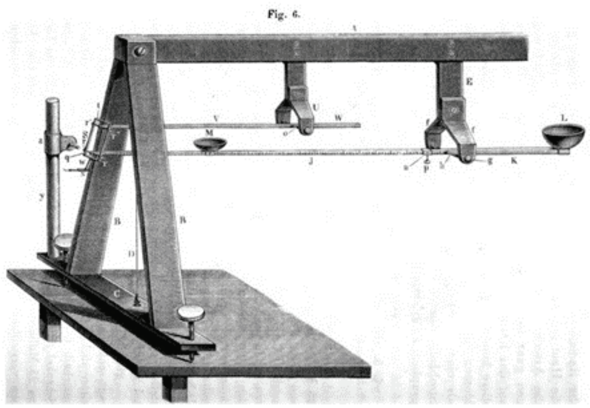

Fig. 1b. Vierordt's sphygmograph [10].

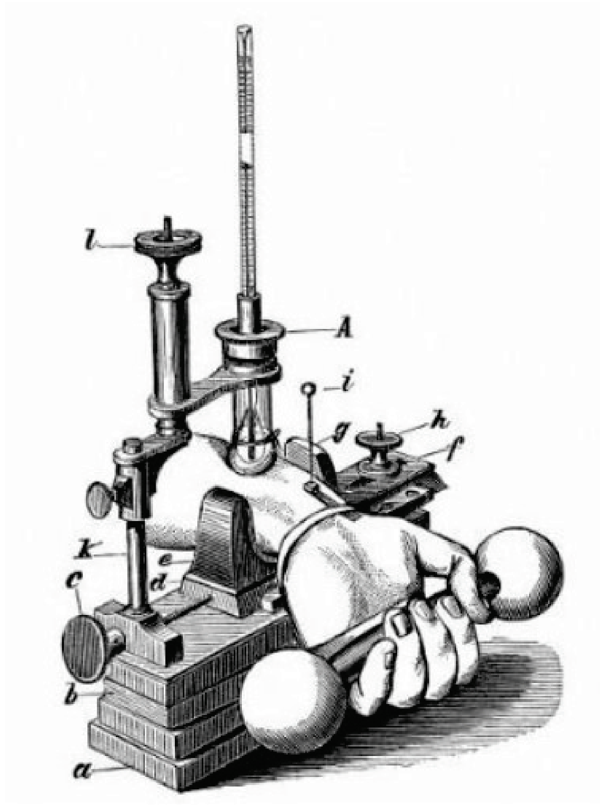

Fig. 2a. Von Basch's sphygmomanometer [11].

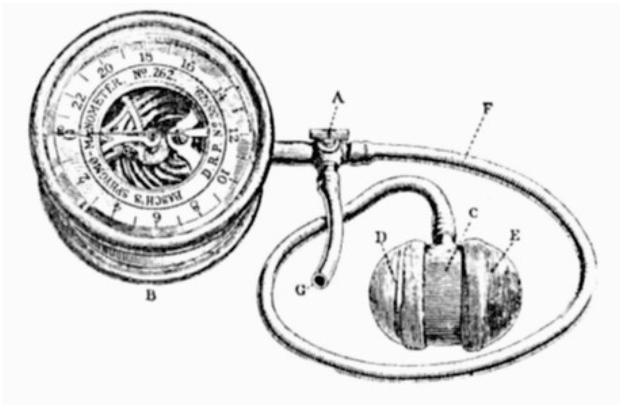

Fig. 2b. Von Basch's aneroid sphygmomanometer [11].

as Hofmann in 1877 [12], who measured BP of different animal species and different ages, he concluded that younger animal individuals have lower arterial blood pressure. Since the value of arterial blood pressure in adult pathologic patients determined invasively by Faivre was around 120 mm Hg, he estimated the value of BP of a healthy adult to be around 200 mm Hg. With this assumption, he calculated that the blood pressure of human newborns could be 111 mm Hg, three-year-old children 138 mm Hg and in 14-year-old individuals 171 mm Hg.

These data were taken up by his son, the physiologist Hermann Vierordt, who published an extensive monograph in Jena in 1893 [13]. In addition to the taken up data from the previously mentioned monograph, he also presented values of blood pressure in the capillaries of the nail bed, changes in BP in the standing position, etc. Interestingly, H. Vierordt also reported blood pressure values (44 and 56 mm Hg) in 4.5 and 10 year old boys in the a. radialis measured by Zadek [14], as well as in the temporal artery in 2-5 year old children with a value of 97-104 mm Hg measured by Eckert [15] using von Basch's sphygmomanometer.

The measurements reported by Zadek and Eckert are probably the first non-invasive blood pressure measurements in children. Zadek, who obtained priority results in blood pressure variability, also confirmed the suitability of using the von Basch's sphygmomanometer using experiments on dogs by simultaneous invasive and noninvasive blood pressure measurements.

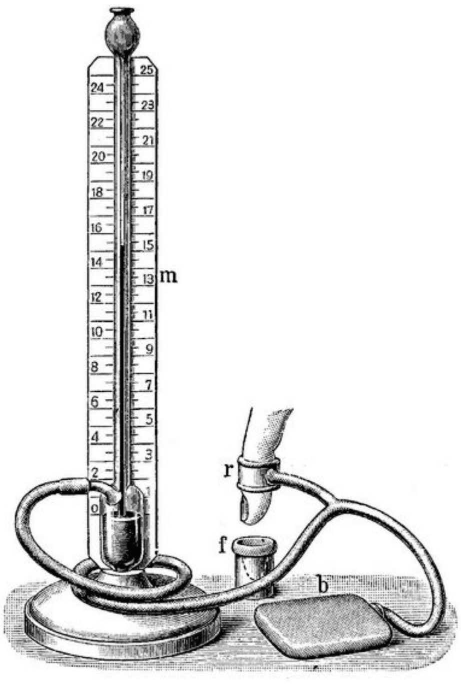


**Fig. 3.** Gärtner's tonometer [16].

Another device used to measure blood pressure at the turn of the 19th and 20th centuries was the Gärtner's tonometer [16]. It was an instrument for measuring the finger BP of an adult by determination of the pressure, expressed by the height of the column of mercury, required to stop the artery pulsation in the finger surrounded by a compressive inflatable ring-cuff (Fig. 3). The decreasing pressure value at which blood flow reappeared in the finger was also taken into account. Gärtner thus gave the basis for the flush method.

In 1902 Neu [17], and in 1906 Trumpp [18] found with Gärtner's tonometer that the systolic pressure in newborns is 75-90 mm Hg. Sladkoff [19], cited by Gundobin [20], used this type of tonometer to measure the BP of 600 children (both newborns and children up to the age of 15 years). He found the average value of 61 mm Hg for the blood pressure of newborns in the first 24 h. He also described an increase in BP with age, especially in the early days and weeks, with a slower rate of rise later in infancy.

*Flush method*

The principle of this method is based on visualizing the return of blood flow by monitoring the color of the finger, forearm, or leg and correlating it with the decreasing pressure in the occluding cuff. The procedure for measuring blood pressure in the extremities of newborns and infants was independently modified in 1952 by Cappe and Pallin [21] and Goldring and Wohltman [22].

Partial ischemization of the finger, upper or lower limb was achieved by gradually squeezing the blood out of the hand or foot by wrapping an elastic bandage or soft rubber starting from the acral parts of the limb. To facilitate drainage, the limb was held above the level of the heart. In more recent blood pressure measurements using this method, Ribeiro *et al.* 2011 [23], used gentle hand compression by the examiner to induce ischemia in the hands of newborns until the skin became pale. However, other authors did not consider this method of ischemia to be sufficient [24].

An occlusion cuff of a blood pressure monitor was then placed over the ischemic part of the limb, inflated to a pressure above the predicted systolic pressure (90-130 mm Hg in newborns).

After the blood flow was stopped, the bandage or rubber band was removed, the limb was kept at heart level, and the pressure in the cuff was slowly reduced at a rate of 4-6 mm Hg every 3-5 s. Simultaneously, the color of the limb and the height of the mercury column were observed to determine the point at which the color changed. The first indication that the blood flow was about to reappear, known as the “flush point”, was the initiation of small oscillations in the mercury column of the tonometer. The maximum oscillations approximately coincided with the height of the mercury column and with the mean arterial pressure [25].

To make the measurement more accurate, two observers were required: one operated the inflation and deflation of the cuff and read the pressure values, while the other observed the flush – the onset of perfusion. The results obtained using this method were limited by edema, hypothermia, and severe anemia [26].

The flush method was mainly used in the middle of the 20th century. Ribeiro *et al.* [23] compared three non-invasive techniques for measuring neonatal BP – the flush method, measurement using pulse oximetry, and the oscillometric method. They concluded that the flush method is relatively accurate and may be useful, especially when blood pressure cannot be accurately detected by the oscillometric method. Despite this statement, the number of available scientific papers using the flush method for measuring blood pressure in newborns has significantly declined after the year 2000.

*Palpation method*

At the turn of the 19th and 20th centuries, the palpation method for measuring blood pressure became prominent. Scipione Riva-Rocci in 1896 [27] used a pneumatic cuff connected to a mercury column, the value of which he increased until the disappearance of the pulse at the a. radialis (Fig. 4). By palpation of the a. radialis and subjective assessment, one detected the moment, and thus the value of systolic pressure, when the pulse disappeared or reappeared as the pressure increased or decreased over or below systolic pressure. The greatest improvement in Riva-Rocci's method of blood pressure measurement was the application of a cuff around the arm, which evenly applied pressure around the limb. This eliminated the most significant error associated with uneven compression of the radial artery using pellets of different sizes. However, the palpation method could not determine diastolic and mean blood pressure, and Riva-Rocci used only a narrow (5 cm) cuff in adults. This error was corrected by von Recklinghausen [28] as early as 1901. By repeated measurements in adult humans, he showed that narrower cuffs provide higher BP values and increasing the cuff width to 12-14 cm no longer affects the measured BP values.

The use of the palpation method in newborns was mainly limited by the problem of pulse palpation at the fine thin a. radialis. Nevertheless, several authors have also used this method in newborns with a preference for palpation of the a. brachialis in the fossa cubiti just below the occlusion cuff.

Reis and Chaloupka in 1923 [29] measured blood pressure by the palpation method on the first and tenth day after birth and found relatively low values – on the first day after birth the mean systolic pressure was 43 (32-58) mm Hg, on the tenth day 78 mm Hg. However, they used too wide cuff in the measurements, which caused artificially low values of measured BP. They found that after deliveries using forceps, traumatized newborns had a higher BP; after cesarean delivery, BP did not differ from that of newborns delivered physiologically.

The issue of cuff width factor was again highlighted by Woodbury *et al.* [4], who found a close correlation between BP values obtained in newborns by the invasive method (measurement in the a. umbilicalis) and the palpation method, but only when a cuff width of 2.5 cm was used.

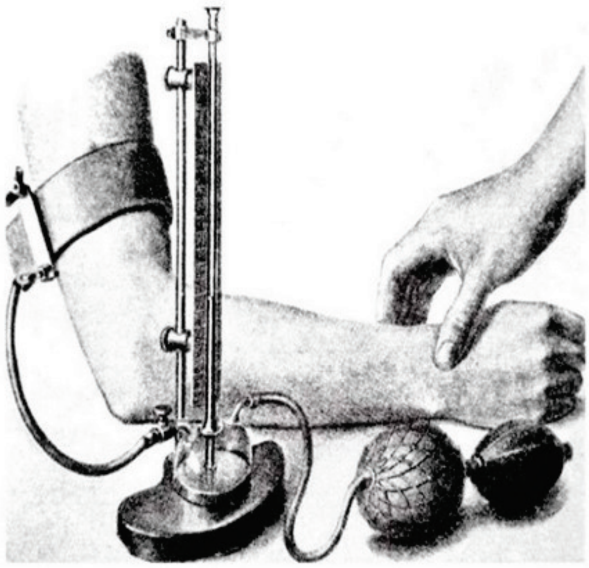

**Fig. 4.** Measurement of systolic blood pressure by the RR method [27].

In the mid-twentieth century, neonatal BP was measured by the palpation method by Holland and Young [30]. They used a 2.5 cm wide cuff and palpation of the pulse at the a. brachialis just below the occlusion (in the fossa cubiti). They calculated the mean of 2-3 systolic BP measurements, which were measured within 1 h after birth and in the later period of life until the 6th month of age. In healthy newborns, the mean BP at birth was 69 mm Hg, and at the 6th month it was 93 mm Hg. Systolic BP in preterm infants was lower than in term infants.

*Methods based on sound detection*

Significant improvements in blood pressure measurement and the determination of diastolic pressure were made by N. S. Korotkov (1874-1920). He published his discovery of the auscultatory method in 1905 in one of the shortest classical scientific papers in the world, one page in length [31,32].

The auscultatory method has also been used in newborns [33]. However, this method without determining the optimal size of the occlusion inflation cuff and for morphological/functional reasons (small arm circumference, vessels, as well as oscillation amplitude) gave only variable values. The obtained BP values were usually lower than those obtained by direct measurement [34,35]. The use of the auscultatory method of measuring blood pressure in newborns and infants may also be hindered by uncontrollable limb movements that may accompany cuff inflation and deflation. Therefore, measurement of BP by auscultatory technique in children from birth to approximately 3 years often fails.

Therefore, physiologists, physicians and engineers, focused on detecting the dynamic state of the vessel under the occluding cuff using the Doppler effect.

In 1957, Shigeo Satomura [36] used the Doppler effect to diagnose cardiovascular anomalies in humans. McCutcheon and Rushmer [37] proposed the use of ultrasound to detect arterial pulsations, and in 1968, Stegal *et al*. [38] constructed an ultrasonic tonometer for measuring BP in adult humans, which could also be used in infants and newborns.

Blood pressure measured using an ultrasound device (e.g. Arteriosonde) has a good correlation with the "gold standard" – values obtained from intra-arterial measurements, especially for systolic blood pressure [39,40], even in newborns [23]. There has been a proven close correlation with systolic pressure values, but determining diastolic pressure was not so reliable.

Czechoslovak scientists and technicians also contributed to the development of blood pressure measurement in newborns using ultrasound methods. The LUD-802 Tesla ultrasonic tonometer was constructed and patented in Tesla Valašské Meziříčí [41]. The set included a portable ultrasound device, a miniature probe, and tonometric cuffs of various widths for children (Fig. 5). The ultrasonic tonometer was used in several clinical and physiological studies [42,43]. Accurate evaluation of blood pressure recordings was made possible by connecting a mercury manometer to an electromanometer in parallel and by recording the output ultrasonic signal [44] (Fig. 6).

Not only ultrasound, but also infrasound, generated by vibration of the vessel wall during occlusion and the subsequent restoration of blood flow, was used for non-invasive measurement of blood pressure in newborns. Detection of infrasonic vibrations of the vessel wall at the time when a bolus of blood enters the occluded collapsed segment after the pressure in the occluding inflation cuff has been reduced below the systolic pressure was detected by the Infrasonde 3000 device. Large vibrations ("flutter") of the artery wall cease at the time the cuff pressure drops below the diastolic pressure [45]. A reasonably accurate systolic pressure value was obtained using the Infrasonde, but the diastolic pressure was significantly underestimated [46,47].

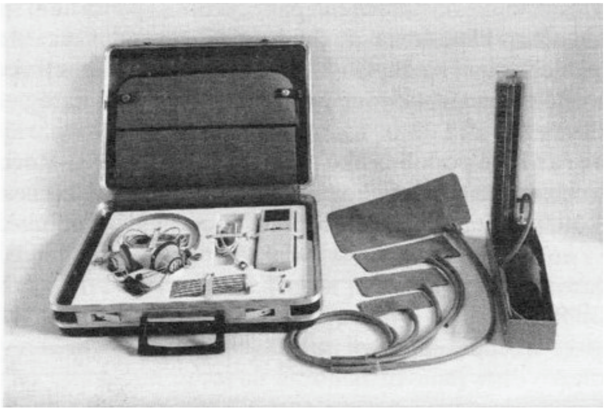

**Fig. 5.** LUD-802 TESLA ultrasound blood pressure measurement set consisting of an ultrasound device with headphones, a miniaturized ultrasound probe that was placed over the artery under the occlusion cuff, a set of cuffs of different sizes and a mercury tonometer [45].

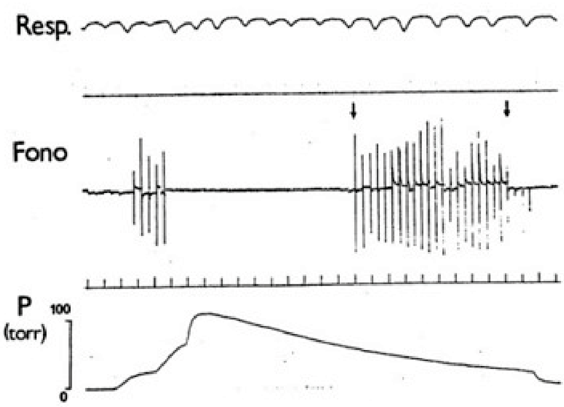


**Fig. 6.** Original record of blood pressure measurement of a premature newborn using a LUD ultrasound tonometer and electromanometer. Upper curve – respiration, lower curve – sound recording, lower curve – cuff pressure recorded by electromanometer.

*Oscillometric methods using mechanical detection of arterial oscillations*

Étienne Jules Marey constructed a manometer in

1876 [48,49] consisting of a glass box filled with water, in which a hand was placed and sealed (principle of a plethysmograph). The box was connected to a water reservoir that allowed for increasing or decreasing the pressure in the box. It also included a mercury manometer and a recording device, which used a tambour writing system and paper for kymographic tracing. By increasing the pressure in the plethysmograph, the amplitude of the sphygmogram changed until the pulsations disappeared. Marey noted that maximum oscillations were transmitted to the water when the counter-pressure was at a level that maximally unloaded the vessel walls throughout the heart cycle. In 1969, Poesy *et al*. (50) confirmed that the point of maximum oscillations actually corresponds to true mean arterial pressure. The device was too complicated, the oscillations were dampened by the physical properties of the mercury and it was unsuitable for measuring blood pressure in newborns and children.

A simple oscillometer for measuring blood pressure, easily applicable to humans, was designed, constructed, and experimentally verified by Hill and Barnard [51] a year after the publication of the palpation method. In 1897, they published a paper describing the construction of an oscillometer for measuring blood pressure in humans. It consisted of an inflatable cuff, a pump, a three-way tap, and a sensitive metal aneroid gauge with a large pointer (Fig. 7). They observed the movements of the aneroid gauge pointer while increasing the pressure in the cuff above the value of the systolic blood pressure, noting the cessation of gauge oscillations, as well as during pressure reduction when the movements of the pointer reappeared. The largest oscillations indicated the value of the mean blood pressure. The authors verified that the pressure value corresponded to the mean blood pressure by conducting experiments with simultaneous blood pressure registration in the femoral artery and blood pressure measurement using the oscillometer in experimental animals. The authors recommended the use of the sphygmomanometer also in children, suggesting to place the cuff on the thigh to measure the blood pressure in the a. femoralis.

Erlanger [52] in 1904 improved the Marey's method by attaching a Riva-Rocci cuff around the upper arm and recording the cuff pressure oscillations with a kymograph. Oscillations appeared at the moment when the external pressure dropped below the intravascular pressure, which determined the systolic pressure. Erlanger considered the cuff pressure value at the sudden attenuation of the oscillations to be the diastolic pressure value.

In 1909, Victor Pachon [53] developed a sophisticated sphygmomanometric oscillometer to measure arterial blood pressure, which was used by physicians until the late 1960s. Pachon used one compartment of the cuff to detect cuff pressure and another compartment for showing cuff pressure (Fig. 8). It was the first device that allowed relatively accurate determination of blood pressure without the use of a stethoscope. At that time, it was believed that the maximum amplitude of oscillation indicated the diastolic blood pressure. Later, it was found that the maximum oscillations corresponded to the cuff pressure, which is equal to the mean arterial pressure.

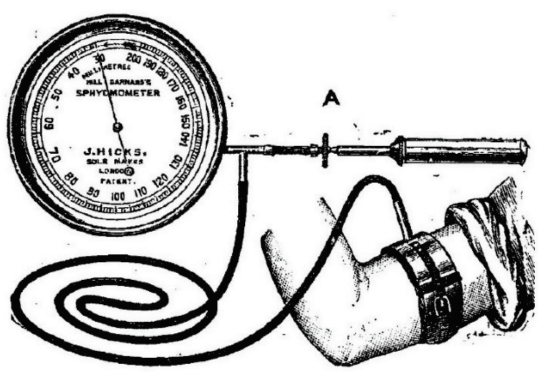


**Fig. 7.** Hill and Barnard sphygmomanometer [51].

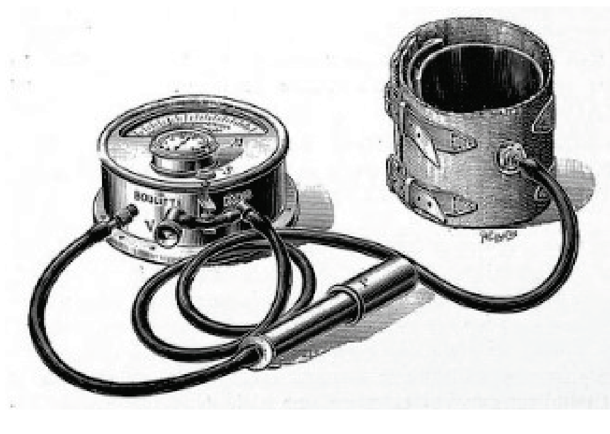

**Fig. 8.** Original drawing of Pachon oscillometer [53].

Automatic measurement of BP by a device based on oscillometric technique was first described by Ramsey in 1979 [54]. A modern modification of the oscillometric method, which is still used in most automatic and semi-automatic electronic pressure gauges, was patented in the USA on 24 January 1984 by Nunn and Beveridge [55]. It utilizes the assessment of pressure oscillations in the cuff caused by the pulse wave using sensors and software. The oscillations begin well above systolic pressure and continue below diastolic, so that systolic and diastolic pressure can only be estimated indirectly according to some empirically derived algorithm [56].

The non-invasive methods, including oscillometric methods, began to be used intensively in children and newborns as early as the beginning of the 20$^{th}$ century, as evidenced by a review of 29 papers published between 1902 and 1926 on the measurement of blood pressure in more than 100 newborns and infants and in several thousand children [57]. The rapid spread of methods for noninvasive BP measurement is evidenced by the affiliations of the papers. There are papers from France, Austria-Hungary, Italy, Germany, USA, UK, Sweden, as well as China and Russia.

In very small children, the oscillometric method was first used in 1912 by Koessler [58]; cited by Kafka [59]. Balard [60-63] as early as 1912 made extensive studies of blood pressure and pulse rate with an oscillometric device in newborns by measuring BP on the upper limb. The first measurement was taken in the first minute after birth and the first cry, then after a quarter of an hour and at the end of the first hour, every two hours for the first 12 h, and then every day until 10 days of age. He found that in newborns the systolic pressure was in the range of 35-55 mm Hg and this increased after the first cry as well as with advancing postnatal age, until the 10$^{th}$ day after birth was observed. Blood pressure as well as pulse rate were higher in the awake state. Ballard also determined diastolic pressure, which was not elevated in the awake state. He attributed the rise in pressure amplitude in the awake state to the increased work of the heart. He measured the body temperature and found that by lowering the temperature, the heart rate decreased in parallel.

At a time when pressure sensors did not exist, the detection of pressure oscillations in the cuff was a crucial problem. Therefore, in addition to the above methods, other methods have been used to detect changes in vessel oscillations and blood flow by cuff occlusion pressure. Ashworth *et al*. [64] introduced *the xylol method*. In this method, a tonometric occlusive cuff was applied to the arm, and a second low-pressure cuff was applied to the wrist area to detect radial artery oscillations. The tube connected to the lower cuff was filled with colored xylol, which began to pulsate with the appearance of a pulse in the radial artery. At that moment, the value of the systolic pressure was read from the mercury manometer connected to the occluding tonometric cuff. The authors reported that the error of this method was ± 4 mm Hg. This method has not found widespread use in clinical practice; it has been used mainly in clinical-physiological studies. For example, Ashworth and Neligan [65] found by the xylol method that newborns in the first hours after birth when the umbilical cord was ligated during delivery had a lower systolic BP (by 10 mm Hg), compared with newborns whose cord was tied later after birth.

*Impedance plethysmography* (reoplethysmo-graphy) for measuring systolic pressure in newborns has been used by Schaffer [66]. Impedance plethysmography records changes in tissue impedance caused by blood flow. After the disappearance of blood flow distal to the occluding cuff after occlusion, the tissue impedance changes cease, and the rheographic curve reappears after the return of flow. Lang and Hilber [67] used electrical impedance plethysmography in the limbs of newborns and infants to determine the optimal width of inflatable cuffs.

Celander and Thunell [68] used a *volumetric plethysmographic method* to measure blood pressure in newborns. Changes in limb volume over a short period of time depend on arterial inflow (and venous outflow). When volume is sensed distally below the occlusive cuff, the first increment of the first arterial inflow determines the systolic pressure value. With a gradual decrease in occlusion pressure, the arterial inflow gradually increases, and the appearance of a maximal inflow given by the cuff pressure value indicates the diastolic pressure value.

Mason and Braunwald [69] used a strain gauge method in adult humans to sense changes in limb volume and thus to measure both blood flow and pressure in the limbs. The sensor was made of an elastic tube filled with mercury placed around the limb. By changing the length and cross-section due to changes in the volume of the limb by inflow and outflow of blood, the electrical resistance values in the sensor were also changed. This method was also attempted by Gundersen and Dahlin [70] to measure the blood pressure of newborns. They constructed a miniaturized cuff and sensor with placement on the finger of the hand. The values correlated with the invasive measurements mainly in term newborns weighing more than 3000 g.

A simpler and more accurate method was found to be *pulse oximetry* [71,72], which was used to determine systolic blood pressure. During cuff inflation, deflation, or both maneuvers, the oximetric waveform dependent on blood flow to the monitored distal part of the limb disappeared and reappeared. These studies using pulse oximetry technique in newborns showed good correlation with direct invasive monitoring, even significantly better compared to values obtained with oscillometric devices. According to Movius *et al*. [71], pulse oximetry provides an alternative non-invasive option for measuring blood pressure in newborns and children without the need for expensive equipment, especially in cases where the oscillometric method is inaccurate due to very low blood pressure.

*Automatic oscillometric blood pressure measurement*

In 1965, Gupta and Scopes published a paper [73] on an automatic oscillometric device that allowed the systolic blood pressure of newborns to be measured and recorded in a non-invasive manner every two minutes for up to 12 h. The device was based on the oscillometric principle with two cuffs: the upper cuff was occluded, the lower cuff inflated to 10 mm Hg was for the detection of vessel oscillations. The pulsations of the vessel wall and the resulting pressure and air volume changes in the lower cuff were detected by a heated thermistor changing the resistance value by temperature changes by moving cooler air through a thin capillary. The electrical signal was transmitted to the recorder. The authors used this device to gain insights into the physiological changes in BP during bottle-feeding, breastfeeding, pacifier use, and changes in body position.

Currently, even in newborns and infants, the most widely used monitor is the Dinamap monitor using cuff pressure oscillation assessment by a sensitive sensor and special software. The original Dinamap oscillometric monitor was an automated oscillotonometer using two cuffs. Modern systems use only one cuff performing both occlusion and sensing functions.

The oscillometric method is popular due to its convenience and ease of use. Comparison of BP values obtained by oscillometric and invasive measurements by meta-analysis of 34 papers [74] showed that mean BP values correlate best. However, it can be inaccurate, for example, in very low birth weight newborns and in babies with low mean arterial pressure [23].

*Continuous non-invasive blood pressure monitoring*

Non-invasive continuous beat-to-beat blood pressure registration is made possible by devices based on the volume-clamp method developed and described by physiologist Jan Peňáz [75] in 1968. Peňáz's method works on the principle of the „unloaded arterial wall“. Arterial pulsation in a finger is detected by a photoplethysmograph under a pressure cuff. The output of the plethysmograph is used to drive a servo-loop, which rapidly changes the cuff pressure to keep the output constant, so that the artery is held in a partially opened state. The cuff pressure is recorded and the obtained values of instantaneous beat-to-beat blood pressure and heart rate are stored in the device's memory, transferred to a computer, and processed by special software [76]. This method gives an accurate estimate of the changes of systolic and diastolic pressure when compared to brachial artery pressure. The Finapres (Ohmeda) device was constructed on this principle, later Finometer, Portapres, Finometer NOVA (FMS) and others.

Their use is appropriate in research, diagnosis and monitoring of adult and pediatric patients. Jagomägi *et al*. [77] and Lemson *et al.* [78] compared the Finapres measurements with the oscillometric method and concluded that each of these methods shows relevant arterial pressure values.

Studies by Drouin *et al*. [79], Andriessen *et al.* [80], Yiallorou *et al.* [81] demonstrated that even in newborns this method can be applied in a modified way (by placing the cuff on the newborn's wrist instead of the finger). The relevance and validity of such a modified method has been verified and proven by comparison with the invasive method after catheterization [80].

In newborns, this methodology is mainly used in clinical physiological studies dealing with short-term beat-to-beat blood pressure and heart rate variability, baroreflex sensitivity and rapid blood pressure reactions to various manoeuvres, stimulations, apnoeic pauses, etc. [81-87].

There are no reports yet on the use of other methods under development for non-invasive continuous blood pressure monitoring, such as applanation tonometry, in newborns and young children.

## Conclusions

The development of methods for measuring blood pressure in adults and later in newborns was determined by the inventions of physicians and physiologists in the field of medicine, as well as engineers on whom technological progress depended (mechanics, electricity, semiconductors, sensors, computers). Multidisciplinary collaboration was crucial in achieving the current state of having different methods for measuring systemic blood pressure in newborns.

The measurement and obtained blood pressure values provide important information about the functional state of the cardiovascular system. However, this information does not inform about the critical perfusion of individual organs, which may differ from the predicted values by regional regulations and the actual state of the organ. Therefore, other methodologies are currently being developed to detect organ perfusion and their oxygenation status, such as new Doppler ultrasound techniques, near-infrared spectroscopy (NIRS), and others. However, these techniques are more complicated and costly, so the measurement and monitoring of blood pressure in humans, even in newborns and young children, remains of clinical and scientific importance.

## Conflict of Interest

There is no conflict of interest.

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