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Scipione Riva-Rocci and the men behind the mercury sphygmomanometer

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SUMMARY

The history of the blood pressure (BP) concept and measurements is described. Many scientists were involved. Among them, major triumphs were achieved by William Harvey during the early 1600s who announced that there is a finite amount of blood that circulated the body in one direction only. In the mid-1700s, Reverend Stephen Hales reported the first invasive measurement in horses and smaller animals. Poiseuille introduced in the early 1800s the mercury hydrodynometer and the mmHg units. Karl von-Vierordt described in 1855 that with enough pressure, the arterial pulse could be obliterated. He also created the sphygmograph, a pulse recorder usable for routine non-invasive monitoring on humans. In 1881, von Basch created the sphygmomanometer and the first non-invasive BP measurements. However, in 1896, Scipione Riva-Rocci developed further the mercury sphygmomanometer, almost as we know it today. The sphygmomanometer could only be used to determine the systolic BP. Observing the pulse disappearance via palpation would only allow the measuring physician to observe the point when the artery was fully constricted. Nikolai Korotkoff was the first to observe the sounds made by the constriction of the artery in 1905.

Keywords: Arterial pressure; blood pressure; history; hypertension; detection and control

The sphygmomanometer, the common blood pressure (BP) measurement apparatus, consisting of an inflatable arm band connected to a mercury manometer was introduced by Scipione Riva-Rocci in 1896 (1–3). Sphygmo is the Greek word for pulse. This device, the standard instrument for measuring BP, led to many new developments in the therapy of hypertension disease.

Scipione Riva-Rocci (Figure 1) was an Italian internist, pathologist and paediatrician, born August 7, 1863, Almese, Piedmont, near the city of Torino. He graduated in medicine and surgery in 1888 from the University of Torino. From 1888 to 1898, he served as assistant lecturer at the propaedeutic medical clinic in Turin directed by Carlo Forlanini (1847–1918) who was the inventor of the technique of artificial pneumothorax for the treatment of pulmonary tuberculosis (3).

In 1894 he graduated in pathology and in 1907 in paediatrics. In 1898, he followed Forlanini to the University of Pavia. Riva-Rocci contributed to the development of Forlanini's method through original physio-pathological research. He demonstrated the importance of the eccentric pressure of the pulmonary alveolus, and he showed that the respiratory function is not substantially endangered in individuals suffering from a reduction of respiratory lung area, particularly in patients with tuberculosis of the lung during pneumothoracic treatment. From 1900 to 1928, he was director and head physician of the Ospedale Civico di Varese, and from 1908 to 1921, he also lectured at the Pediatric Clinic of Pavia University. Riva-Rocci died on March 15, 1937 in Rapallo, Liguria.

His fundamental contribution was the mercury sphygmomanometer, which is easy to use and gives sufficiently reliable results. On December 10, 1896, Riva-Rocci published the first of four articles in the Gazzetta Medica di Torino (4). The first two were about a new sphygmomanometer, and the others were on the technique (5,6). The Riva-Rocci sphygmomanometer contained an elastic inflatable cuff that was placed over the upper arm to constrict the brachial artery, a rubber bulb to inflate the cuff and a glass manometer filled with mercury to measure the cuff pressure (Figure 2). Riva-Rocci measured the systolic pressure by registering the cuff pressure at which the radial pulse was obliterated as determined by palpation. The palpation technique did not allow the measurement of diastolic pressure (7).

A major role in spreading the use of the instrument was played by the American neurosurgeon Harvey Cushing who

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Figure 1 Scipione Riva-Rocci. August 7, 1863–March 15, 1937

helped bring the mercury sphygmomanometer to the attention of the world. On a visit to Pavia in 1901, Cushing found Riva-Rocci's sphygmomanometer a valuable means of reducing mortality from anaesthesia, especially during intracranial surgery (7).

Riva-Rocci, however, did not create the first sphygmomanometer, but his ingenious simple idea offered medical practitioners an efficient method for obtaining relatively accurate readings.

BP IN THE ERA PRIOR TO RIVA-ROCCI (1,5–7)

130–200 AD Galen

The ancient Greek physician Galen first proposed the existence of blood in the human body. Building on ideas conceived by Hippocrates, the body was comprised of three systems. The brain and nerves were responsible for sensation and thought. The blood and arteries filled the body with life-giving energy. He also theorises that blood travels backward and forward in unconnected veins and arteries.

Early 1600s: Harvey Introduces the Concept of One-Way Circulation

It was not until 1616 when William Harvey announced that Galen was wrong in his assertion that the heart constantly produced blood. Instead, he proposed that there was a finite amount of blood that circulated the body in one direction only. Interestingly, Harvey was neither the only nor the first to question Galen's ideas. The Egyptians knew that blood

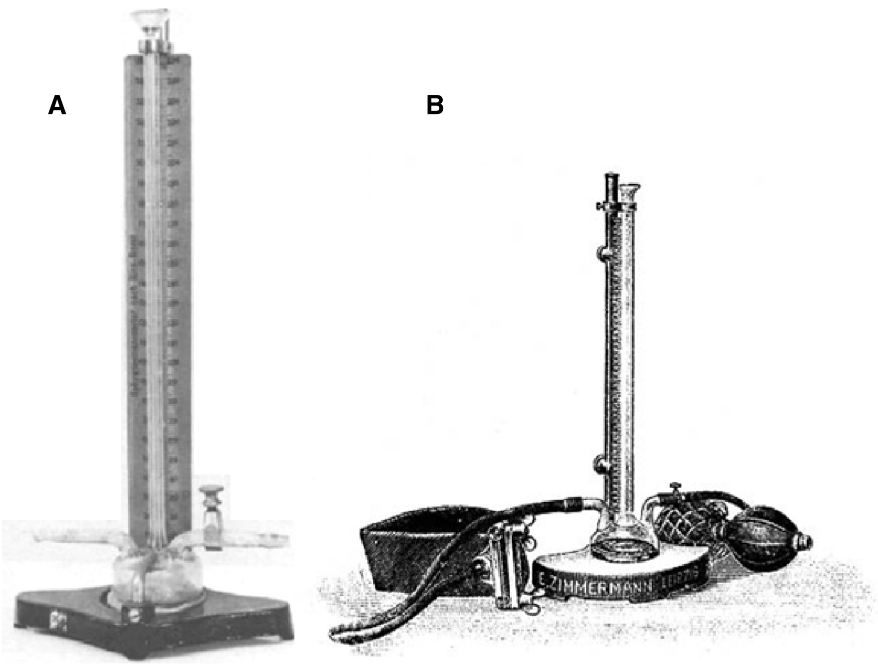

Figure 2 The Riva-Rocci mercury manometer. (A – picture, B – diagram). This is much like the modern device used to measure arterial blood pressure. There is a mercury manometer and a silk-covered rubber sleeve which can be tied around the upper arm, closed with a steel clamp and filled with air by a rubber squeeze bag. Source of illustration: Zimmermann, E. (1903). XVIII. Preis-Liste über psychologische und physiologische Apparate. Leipzig: Eduard Zimmermann

flowed through the body and used leeches to unblock what they thought were passages of blood.

Mid-1700s: Stephen Hales – First Invasive Measurement

The first recorded instance of the measurement of BP was in 1733 by the Reverend Stephen Hales who was born on September 1677 in Bekesbourne, Kent, England. While a divinity student at Corpus Christi College, Cambridge, he studied science, particularly botany and chemistry. Ordained in 1703, he was appointed in 1709 to the parish of Teddington, where he remained until his death on January 4th, 1761.

Hales introduced new techniques of measurement in the study of plant physiology, including rate of water vapour emitted by plants, the direction in which sap flows in plants and the sap's pressure, the rates of growth of shoots and leaves and the pressure roots exert on sap and investigated plant respiration. As an inventor, he developed an artificial ventilator (a modified organ bellows) that could convey fresh air into prisons, ships' holds and granaries.

Reverend Hales spent many years recording the BPs of animals. He inserted one end of a brass pipe into the ligated left crural artery of a horse, and to the other end, he attached a vertically positioned glass tube, nine feet in length. On untying the ligature on the artery, blood rose in the tube to a height of 8 feet 3 inches above the left ventricle of the heart (Figure 3). This was the first recorded estimation of BP. With this, he determined the quantity of circulating blood in the horse and observed that the jugular venous pressure was 12 inches when the horse was at rest and 52 inches when excited. In addition, he was able to measure the capacity of the left ventricle of the heart, the output of the heart per minute and the speed and resistance to flow of blood in the vessels. One of his more exotic experiments was Leonardo da Vinci's method of injecting wax into the heart chambers of cadavers to determine the capacity of these chambers by measuring the volume of the casts.

He also demonstrated that the pulse rate was more rapid in small animals than large animals and that BP was proportionate to the size of the animal. His work was published in Hæmastaticks and was the most important contribution to the physiology of blood circulation since that of William Harvey. Yet, his technique was invasive and highly inappropriate for clinical use.

Early 1800s: Poiseuille Introduced Mercury Hydrodynometer

John Leonard Marie Poisseuille (1799–1869) known for his law of fluid flow, which is the analogue of Ohm's law, introduced the units – mmHg, which he described in his medical school thesis in 1828. These units are still being used today to measure BP by using the mercury manometer. The use of mercury allowed for smaller height of column needed for measurements. Poisseuille improved upon the original BP-measuring apparatus by substituting the short tube of a mercury manometer for the inconveniently long tube used by Hales. Connection with the artery was established by means of a hollow lead tube filled with potassium carbonate, to prevent coagulation. This was Posseuille's haemodynamometer of 1828, with which he showed that BP rises and falls with expiration and inspiration.

The search for a more standardised method of determining and visually displaying the movement of the blood around the body led to the development of sphygmographs, sphygmomanometers and the less successful sphygmometers.

1846 Carl Ludwig's Recording Cylinder

Karl Ludwig (1816–1895) added a float to the mercury manometer with a connecting arm, which inscribed arterial pulse wave on a recording cylinder that gave a permanent record. Ludwig's kymograph consisted of a U-shaped manometer tube connected to a brass pipe cannula into the artery (Figure 4). The manometer tube had an ivory float onto which a rod with a quill was attached. This quill would sketch onto a rotating drum, and hence the name 'kymograph', 'wave writer' in Greek. However BP could still only be measured by invasive means.

Figure 3 Reverend Hales recording the horse's blood pressure

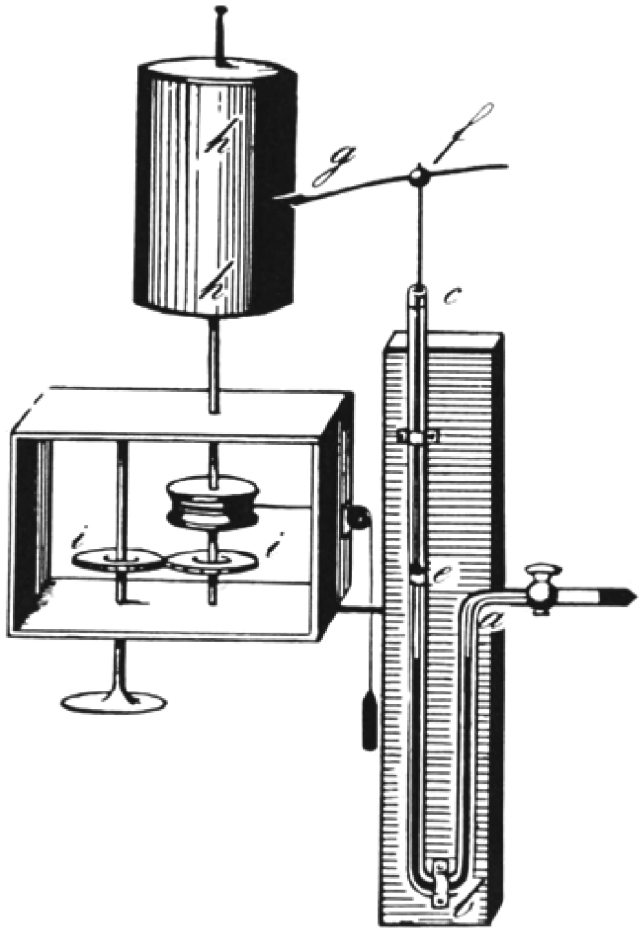

Figure 4 Ludwig's kymograph

1855 Vierordt – External Pressure May Obliterate Blood Flow

The lack of a non-invasive method of determining this new idea of BP lead to many physicians working in this field. One such man, Karl von Vierordt (1818–1884), described in 1855 that with enough pressure, the arterial pulse could be obliterated. Vierordt studied at the universities of Berlin, Göttingen, Vienna and Heidelberg and started a practice at Karlsruhe, Germany in 1842. He developed techniques and instruments for the measurement of various aspects of blood and its circulation. One of Vierordt's early discoveries in 1851 was an exact method of making the red blood cell count. He also devised the haemotachometer, an instrument that monitored the velocity of blood flow. Other research included spectrographic analyses of haemoglobin solutions, bile and urine and studies of respiration and sound conduction.

In 1854, he created the sphygmograph, a pulse recorder usable for routine non-invasive monitoring on humans. Sphygmographs worked by transmitting the movement of the pulse to a long lever that traced a curve onto prepared paper. By adding weights to little pans attached to a lever, he attempted to estimate the BP. His instrument was cumbersome and his measurements inexact, but he established the principle that the estimation of BP can be accomplished by measuring the outside pressure necessary to obliterate the pulse – a method we employ even today.

1860: Étienne-Jules Marey – the First Practical Version of the Sphygmograph

Etienne Jules Marey (1830–1904), a French physician/cinematographer, developed this idea further in 1860. He devised on the sphygmograph and enabled recording graphically the features of the pulse and variations in BP. His basic instrument, with modifications, is still used today. His sphygmograph could accurately measure the pulse rate but was very unreliable in determining the BP. Doctors found the sphygmograph cumbersome and difficult to use accurately – as well as intimidating for the patient. However, the ability to see variations and abnormalities in the circulation of blood and the heartbeat was of enormous value to the development of experimental physiology and cardiology.

Marey wrote extensively on the circulation of the blood, cholera, experimental physiology and graphic methods in physiology. He also contributed to the development of the motion picture. To study the flight of birds, he invented a camera in 1882 with magazine plates that recorded a series of photographs; the pictures could be combined to represent movements. In 1894, he adapted the motion-picture camera to the microscope.

1881: Robert Ellis Dudgeon – Portable Sphygmograph

In 1881, the English physician and homeopath, Robert Ellis Dudgeon (1820–1904) introduced a new, highly portable sphygmograph. Dudgeon's sphygmograph was strapped to the wrist (Figure 5). The pulse at the wrist caused a metal strip to move a stylus, transmitting a record of the pulse onto smoked paper. Dudgeon's instrument quickly became popular, as it was compact and easy to use. The sphygmograph traces an undulating line, which represents a record of BP and pulse over time.

1880s: von Basch: The Sphygmomanometer – First Non-Invasive BP Measurements

All the above methods required the placing of a tube into an artery and hence were not practical for routine clinical use. The first instrument which did not necessitate puncturing the skin was devised in 1880. The Austrian physician Samuel Siegfried Karl Ritter von Basch (1837–1905) was the first to measure BP non-invasively. He was born in Prague September 9, 1837; best known as the body physician of the emperor Maximilian of Mexico. Basch was educated at

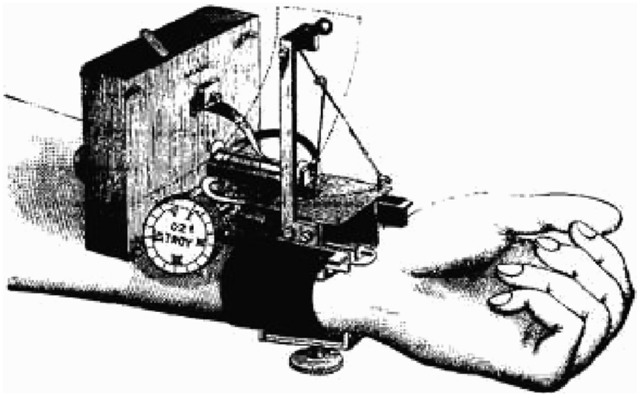

Figure 5 Dudgeon's sphygmograph strapped to the wrist

the universities of Prague and Vienna. In 1857, he studied chemistry, in Vienna, and 5 years later began the practice of medicine. Between 1862 and 1865, he was assistant lecturer at the University of Vienna. He was appointed chief surgeon of the military hospital at Pueblo, Mexico, and soon after, he was called to Maximilian's side, remaining with the unfortunate monarch for 10 months, until his death, June 19, 1867. After the execution of Maximilian, he took charge of the body and returned to Austria. In 1870, Basch was appointed lecturer on experimental pathology at the University of Vienna and in 1877 as assistant professor. He was ennobled by Emperor Franz Joseph for his share in Maximilian's enterprise.

He fabricated successively three models of sphygmomanometers. The first which was invented in 1881, with a mercury column, proved to be the most practical and useful. His sphygmomanometer consisted of a water-filled bag connected to a manometer. The manometer was used to determine the pressure required to obliterate the arterial pulse. Direct measurement of BP by catheterisation confirmed that von Basch's design would allow a non-invasive method to measure BP. Feeling for the pulse on the skin above the artery was used to determine when the arterial pulse disappeared.

However von Basch's design, although it required no surgical incision, was inefficient and never won a keen following. Many physicians questioned the medial usefulness of information about the BP or were sceptical of new technology. This did not stop some from attempting to produce a more useful device. A spring-based sphygmomanometer won some support, but they were difficult to calibrate and were very unreliable when dealing with acutely ill patients.

In 1896, Scipione Riva-Rocci developed the mercury sphygmomanometer.

BP IN THE ERA POST RIVA-ROCCI

Soon after Riva-Rocci's technique was described, Hill and Barnard [7] in England in 1897 reported an apparatus with an arm-encircling inflatable cuff and a needle pressure gauge that allowed measurement of the diastolic pressure by the oscillatory method. This method used the oscillations transmitted to the gauge, as the pulse wave came through the compressed artery. When the cuff pressure was reduced slowly from the suprasystolic pressure, the appearance of definitive oscillations denoted the systolic pressure, whereas the change from maximal oscillations to smaller ones denoted the diastolic pressure. In 1900, von Recklinghausen increased width of the cuff from 5 to 13 cm.

1905: Korotkoff's Sounds

The sphygmomanometer could only be used to determine the systolic BP. Observing the pulse disappearance via palpitation would only allow the measuring physician to observe the point when the artery was fully constricted. Nikolai Korotkoff was the first to observe the sounds made by the constriction of the artery in 1905 (8-10).

Korotkoff was born in 1874 in a merchant family; he received his high school diploma in 1893 from the Kursk Gymnasium, and in 1898, he graduated from the Moscow University Medical School. After graduation, he worked in Moscow in the Department of Surgery. During the Boxer Rebellion in China in 1900, he was sent by the University to the far East as a physician for the Red Cross. In 1902, Korotkoff completed his residency and started working as an assistant at the Military Medical Academy in Saint Petersburg in the Women's Section of the clinic headed by Professor Sergei P. Fedorov. During the Russian–Japanese War (1904–1905), he was directed to Harbin, NorthEast China, where he worked as a physician in different hospitals. From 1908 to 1909, he worked in Siberia as a physician in the Vitemsk-Oleklinsk region of Russia. During World War I, Korotkoff worked in the military hospital in the town of Tsarskoye-Selo, Russia. After the 1917 revolution in Russia, he became the senior physician in a major hospital in Petrograd (Saint Petersburg). Korotkoff died in 1920; the cause of his death is unknown.

His education and experience in treating those wounded in battle led Korotkoff to study damage to major arteries. These studies resulted in his discovery of the new method of arterial BP measurement. It is worth noting that the idea for the new method to measure BP was born during the Russian–Japanese War. Korotkoff was working to solve the problem that was first formulated as early as 1832, 'Can the Ligation of the Abdominal Aorta During Aneurism in Groin Region Be Performed Easily and Safely?' While treating wounded soldiers who had aneurysms, Korotkoff set a goal to find indications that would allow the surgeon to predict an outcome of ligation of arteries of the traumatised limbs, i.e. to predict whether the limb would recover or die after surgery. While attempting to resolve this problem, he systematically listened to the arteries to estimate the potential strength of arterial collaterals after a major vessel of the wounded limb had been ligated. In his studies, Korotkoff used a stethoscope and the apparatus proposed by Riva-Rocci in Italy in 1896.

He established that certain specific sounds could be heard during the decompression of the arteries. This auscultatory method proved to be more reliable than the previous palpitation techniques and thus became the standard practice. This specific phenomenon, known in world literature as 'Korotkoff sounds', became the basis of the new method of BP measurement.

The Future

The future of the mercury sphygmomanometer, that led to many new developments in the therapy of hypertension, is unclear. This instrument may disappear as we know it today (11). There are several reasons for this:

Mercury will probably be banned from hospital use because of the danger of toxicity. The mercury thermometer has already been replaced in many countries, and in Sweden and the Netherlands, the use of mercury is no longer permitted in hospitals. This is expected to happen in more countries. The greatest concern is its toxic effects on the environment. Mercury is a persistent and bioaccumable toxic substance that negatively affects the environment. The many tons of mercury supplied for the manufacture of sphygmomanometers and then distributed throughout the world to hospitals and other health facilities will eventually find its way back into the environment through evaporation, sewage or in solid waste, most seriously damaging the marine environment. It may accumulate in soil and in sediments thereby entering the food chain.

Accurate automated devices are now available to replace the mercury sphygmomanometer, and these devices may be used in the hospital, office settings and as home monitoring (9). The potential advantages of home monitoring include the availability of multiple recordings throughout the waking period taken over many days, which may reduce white coat effect and misinterpretation of measurement variability. Importantly, home BP measurement also involves the patient more closely in the management of their own BP. Values from home measurements tend to be lower than clinic levels.

However, healthcare providers should use only devices that have been independently validated against the relevant protocols. Several issues should be noted. Firstly, the available automated devices were designed for self measurement of BP, and it should not be assumed that they will be suited for clinical use, although some are being used successfully in hospital practice and in several major hypertension studies. Secondly, oscillometric techniques cannot measure BP in all situations, particularly in patients with arrhythmias, such as rapid atrial fibrillation, but there are also individuals in whom these devices cannot measure BP for reasons that are not always apparent. Thirdly, these devices depend on algorithmic methods. To ensure that new devices conform with recommended validation protocols, the mercury sphygmomanometer will have to be retained as a gold standard in designated laboratories.

Aneroid sphygmomanometers register pressure through a bellows and lever system, which is mechanically more intricate than the mercury reservoir and column. The jolts and bumps of everyday use affect their accuracy; they lose accuracy over time, usually leading to false low readings with the consequent underestimation of BP. They are therefore less accurate in use than mercury sphygmomanometers. Central arterial pressure, measured close to the heart, may be of more patho-physiological importance than conventional non-invasive cuff BP (12). The technique of applanation tonometry using SphygmoCor has been proposed as a non-invasive method of estimating central pressure. This relies on mathematically derived generalised transfer functions. The role and status of this method will depend on future studies.

With the introduction of 24-h ambulatory BP monitoring (ABPM) into clinical practice, more reliance is being placed on diurnal changes in BP than on casual measurement of BP levels (9). ABPM provides information about BP during daily activities and sleep. These devices use either a microphone to measure Korotkoff sounds or a cuff that senses arterial waves using oscillometric techniques. Twenty-four hour BP monitoring provides multiple readings during all of a patient's activities. While office BP values have been used in the numerous studies that have established the risks associated with an elevated BP and the benefits of lowering BP, office measurements have some shortcomings. For example, a white-coat effect (increase in BP primarily in the medicalcare environment) is noted in as many as 20–35% of patients diagnosed with hypertension. The level of BP measurement using ABPM correlates better than office measurements with target organ injury. ABPM also provides a measure of the percentage of BP readings that are elevated, the overall BP load and the extent of BP fall during sleep. It was reported recently that ABPM patients whose 24-h BP exceeded 135/85 mmHg were nearly twice as likely to have a cardiovascular event as those with 24-h mean BPs <135/85 mmHg, irrespective of the level of the office BP (13, 14).

Self monitoring of BP at home and work is a practical approach to assess differences between office and out-of-office BP prior to consideration of ABPM. For those whose out-of-office BPs are consistently <130/80 mmHg despite an elevated office BP and who lack evidence of target organ disease, 24-h monitoring or drug therapy can be avoided (9).

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