ISSN 2229-5518

Can Blood Pressure be Measured at all & Can Doctors Rely on such Measurements?

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Abstract — 'Blood pressure' is considered as the most important parameter for diagnosis of cardio vascular and various other diseases. The basic question for any fluid dynamycist is whether Blood Pressure inside human arteries can be measured at all and if so, how accurate can it be? Also, how good is the Blood Pressure standard? This question arises primarily because of the great difficulty in measuring static pressure in a flowing fluid even in engineering systems. More importantly, medical professionals consider hypertension as the most important cause of cardiovascular diseases, but still have not questioned seriously the basis of diagnosing a person as hypertensive or not! The main issue boils down to the question as to who is responsible for raising concerns and solving the serious problems with BP diagnosis. This paper lays out in detail, the important issues from the point of view of the fundamental sciences and the present day technology. It not only questions the present day techniques and standards used for diagnosis but also the newer techniques employing Pulse Wave Velocity, PTT, PPG, etc. which are being proposed and developed.

Index Terms— Blood Pressure, Cannula, Gold Standard, Hypertension, PPG, PTT, Pulse Wave Velocity, Sphygmomanometers, Uncertainty

1. INTRODUCTION

If one asks the question, what is being measured as BP for diagnostic purposes; the answer should surprise anyone, when they find out that physicians in primary care practice measure "static pressure" using sphygmomanometer and surgeons measure "total pressure" in hospitals using a cannula! Even though, both techniques have serious draw backs concerning its own accuracy, it is even more surprising to find that surgeons compare the two readings to ascertain the reliability of the cannula measurement, despite the fact that the two measurements yield different parameters. Even if the measurements are accurate, cannula measures the total pressure which is the sum of the static and dynamic pressures in the flowing blood, while sphygmomanometer measures wall static pressure, which is the static pressure exerted by the flowing blood on the arterial wall. Both of them are different. It is like comparing apple to orange!

Why is it so complicated, when pressure is a very common parameter talked about and measured by engineers (Ref: Bellur, V. P., and Shiva Prasad, B. G., 2013 & 2015)? The answer lies in the fact that unlike engineering systems, one cannot drill a hole and/or put a thin, flexible, pressure sensor flush with the inner surface of the brachial or any other artery to measure blood pressure! Hence, Sphygmomanometry, an indirect technique, uses a transducer on the arm to measure the turbulent peaks (Systolic & Diastolic) of wall static pressure inside the brachial artery. This technique completely ignores the impedance (compliance) of the large mass of viscoelastic tissue, secondary arteries, veins, etc., inside the arm, surrounding the small brachial artery! Hana Tolonen et al have not only identified various factors affecting accurate measurement of BP but also presented a need for standardization of BP measurement process and also discussed the challenges in implementing such protocols. They have indicated errors which could be as high as 30 mms to 50 mms of Hg in some cases. Joel Handler (2009) has quantified some measurement uncertainties in the procedure used in clinics during BP measurement in addition to the problem of white coat hypertension all of which could result in 5 to 50 mms of Hg [see Fig. (1)] inaccuracy.

Factors affecting Accuracy	Systolic/Diastolic BP Discrepancy (mmHg)
Talking or active listening	10/10
Distended bladder	15/10
Cuff over clothing	5–50
Cuff too small	10/2–8
Smoking within 30 minutes	6–20

Ref: Table 1 - Joel Handler, Permanente Journal, 2009 Summer; 13(3): 51–54. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2911816/ 3/10

Fig. (1): Some factors Affecting Accuracy of Blood Pressure Measurement with Sphygmomanometer

Based on a study of a few million measurements, he concluded that about 25% patients could escape treatment, while about 30% could be prescribed unnecessary medication, even though they did not have any intrinsic cardiovascular problems. Both of those outcomes are not healthy.

In a direct, invasive technique, Doctors do make a hole and insert a Cannula inside an artery to measure blood pressure. Unfortunately, even though surgeons consider this as the Gold Standard for blood pressure measurement, it cannot be relied upon for any quantitative assessment not only because it is invasive and changes the flow field, but also due to problems of alignment with flow direction, wall interference effects, etc. Hence surgeons always try to corroborate Cannula measurement with sphygmomanometry for diagnostic purposes. Even in this direct technique, one should not ignore the turbulent nature of the cardiopulmonary system and the uncertainty due to the dependence of the blood flow on anatomy, physiology and neuro-mechanics. Kathrina Siaron et al (2020) report the dependence of blood pressure on even the location of measurement. Location dependence is understandable not only because of the resistance of the arteries to fluid flow but also because of the dynamics of wave interaction in the complex arterial passages. They demonstrated such location dependence by measuring BP using both sphygmomanometry & intra-arterial probe simultaneously and at multiple locations (arm, wrist & thigh) also on a group of patients with neurological problems. They suggested the need for developing treatment protocols based on the location and method of measurement. Noa Kallioinen et al (2017) have presented an extensive review of the various types of problems in BP measurement and discussed the underlying causes. They have also identified the directional biases caused by those factors. They identified more than 25 factors, concluded that errors could be as high as 23 to 33 mms of Hg and the net effect could be cumulative and could lead to highly erroneous results. Hence they recommended abandoning assigning numbers and instead using dots and charts to describe BP results. Consequently they suggested changing the BP diagnosis standards also to range and chart based rather than quantitative values. One should note that all these factors become more important in an emergency situation. However, one cannot merely blame the doctors alone for employing such measurement techniques with large degrees of uncertainty and serious consequences on human health without exposing all the deficiencies and raising serious concerns. However, lack of alternative techniques cannot be claimed as a reason for continuing their use as it could even lead to fatal consequences in many cases. On the other hand, one should convince the medical community by explaining that protecting the body by physical and mental exercises like yoga, etc. which also appears to be gaining ground as a modern day practice is a viable alternative compared to such unreliable measurements, diagnosis and fateful results!

Since the basic measurement technique of Sphygmomanometry itself is highly questionable, and the "Gold Standard" used by medical professionals for Blood Pressure diagnosis is based on measurements done using Sphygmomaonometry, what credibility can exist with such standards!! Perhaps there is an issue also concerning what is treated as a "gold standard" in BP measurement. Some surgeons think measurement using Cannula as a Gold Standard, since it is a direct method of measurement and can measure its variation continuously, even though they themselves do not have the confidence in those measurements and rely upon sphygmomanometry for validation! However, physicians think that Sphygmomanometer, which can easily measure the much needed peak pressures on the arterial wall, which was contrived first and has the benefit of being non-invasive and hence easily acceptable and less expensive should be considered as the gold standard for diagnosis. Also, the BP standard, which is the "Gold Standard" used by both physicians and surgeons for diagnosis was derived using sphygmomanometry and hence many doctors like to consider that as the "Gold Standard". Irrespectively, since systolic and diastolic pressures are closely connected with heart health & human health, wrong diagnosis either due to wrong measurement or use of improper standard for diagnosis leading to use of unnecessary or wrong medication is bound to affect heart health by affecting the elasticity and the resilience of the heart muscles and even arteries. Could the large number of deaths from heart failure and other diseases be linked to the side effects of improper blood pressure medication? Vivekram Bellur & B. G. Shiva Prasad (2020) raised such questions based on their conclusion concerning the use of highly questionable and inaccurate technique for arriving at such "Gold Standard" for Blood Pressure diagnosis.

This paper not only raises urgent and serious concerns about the use of present day techniques for Blood Pressure measurement and also its "Gold Standard" used in medical diagnosis & treatment including surgery but also questions whether the proposed modern day techniques using pulse wave velocity measurement, applanation tonometry, photo plethysmography, etc., can replace them and satisfy the need for accurate measurements?

2. HISTORY OF BLOOD PRESSURE MEASUREMENT & STANDARDS

Heart & Brain are the most important organs of a human being. Failure of either organ leads to the death of a person. Hence human health and wellbeing are determined by the healthy functioning of the Brain & Heart. Heart supplies the nutrients to the brain and the brain controls the proper functioning of the heart. They are mutually interdependent.

Unlike the brain, the human heart has mechanical analogues like the positive displacement pump and hence understanding the anatomy and physiology of the heart has become much easier. This has led to lot of research not only in understanding the functioning of the heart, but also for repairing its parts and even replacing the entire human heart with a mechanical pump or another human or animal (baboon, pig as in the latest technique of Xenotransplantation) heart.

To understand any system one should be able to define the important parameters and be able to measure them. Since the important function of the heart is to pump blood to all parts of the body, the energy (potential & kinetic) imparted to the blood during every stroke of the heart and the volume of blood pumped become important parameters. In fact, research for developing techniques of measurement of the blood flow parameters was initially promoted about a century ago by insurance companies in U. S. who were looking for means to ascertain human health for assessing the insurance premium for their customers. Karatkoff and Rocci came up with an idea to characterize the blood flow by the maximum and minimum pressures attained by the blood as it is pumped in to the aortic chamber. Systolic and diastolic pressures were the names assigned to the two peaks. They along with others came up with a technique of measuring the pressure exerted on the arterial wall (essentially the wall static pressure on the arterial wall) by correlating it with the pressure transmitted to the outside of the arm and measuring it with a transducer placed over the arm. This lead to the invention of sphygmomanometry. The science of fluid mechanics has advanced very much since then and that has raised lot of questions concerning the correlation of the pressure exerted on the arterial wall with the pressure inside the cuff, which is measured outside the arm. In fact, the arterial pressure not only varies continuously both in amplitude and phase as it flows along the resistive passages from the aortic chamber to the tips of the arteries above and below the heart but also in a turbulent fashion due to the presence of the inherent physiological regulatory system. Hence where, when and what type of pressure need to be measured is itself another fundamental question? Should it not be at the aortic chamber itself? If so, is it possible to measure the pressure inside the aortic chamber accurately?

For sphygmomanometry, two techniques of measurement, auscultatory & oscillatory were devised. Irrespectively, the basic questions concerning correlating the arterial pressure to the pressure measured around the arm and hence its credibility also remains same for both of them. The basic reason being that the compliance of the mass of tissue, muscles, etc. surrounding the artery not only depends on anatomy but also varies with physiology, and neuromechanics in a turbulent manner. One can actually devise a simple experiment to demonstrate this poor correlation by embedding a thin polyethylene tube inside a soft rubber pipe covered with a cuff like chamber maintained at a constant pressure; blowing air through the tube in the form of pulses and measuring the wall static pressure, inside the tube and on the pipe simultaneously at the same axial position and comparing the two. One should check how the difference in pressure at the two locations vary with the material of the pipe and the tube representing their compliances or impedances.

The other technique of measuring the BP by surgeons and emergency physicians is by inserting a catheter or cannula into an artery and directly measuring the pressure. However, this technique cannot measure the static pressure either in the flowing fluid or at the wall as measured by the sphygmomanometer and hence cannot be compared or cross checked for verifying the accuracy. The cannula measures the total pressure which represents the sum of potential and kinetic energies of the flowing blood, instead of the sphygmomanometer which measures the potential energy only, at the wall. However, surprisingly, it appears to be the normal practice to use sphygmomanometer for cross checking, which is an intentionally flawed practice and should be treated as a serious ethical issue. The cannula measures total pressure and that too its degree of uncertainty is quite high for the following reasons: (i) the invasiveness is extremely large because of the small ratio of the diameter of the artery to that of the cannula; (ii) the difficulty in aligning the cannula with the flow direction, which leads to measuring only a component of the total pressure; (iii) the proximity of the arterial wall to the cannula, which not only introduces wall interference effects but also adds to the flow invasiveness. In addition, for a patient in an emergency situation, the blood flow becomes more turbulent and the difficulty in inserting and correctly locating and aligning the cannula becomes much greater. Although the cannula being a direct measurement technique is considered as a gold standard for BP by surgeons, it cannot be used as a routine measurement tool and was also not used for arriving at the "Gold standard" for blood pressure diagnosis. The degree of difficulty and inaccuracy due to the above reasons further makes it an improper primary tool for use in setting standards.

Hence the more ancient sphygmomanometer, was used as the primary tool for setting standards for BP diagnosis and due to the large uncertainty inherent in the basic technique itself, the usefulness of such standards is being questioned as a serious issue in this paper also. This author is not only reiterating and raising additional questions concerning the techniques but also the veracity and usefulness of the "Gold Standard" which is being used since a long time for diagnosis of hyper & hypotension and other cardiovascular diseases caused by abnormal blood pressure. This author is surprised why the medical community has not questioned the use of such "Gold Standard" even though serious concerns have been raised concerning the measurement of BP. One cannot be consoled by the fact that a large number of samples were used in arriving at the standards as that cannot improve the accuracy of the measurement and the standards when the basic measurement technique itself is not accurate. Also, one cannot dismiss the serious concerns raised by the mere lack of an alternative technique for measurement and diagnosis, since the societal cost from wrong diagnosis leading to fatalities appears to be extremely high.

3. PROBLEMS WITH PROPOSED TECHNIQUES

Despite serious questions raised by many researchers including the alarm raised by this author (see Vivekram Bellur & Shiva Prasad, 2020) there appears to be not only hesitancy but also opposition from the medical community to question the use of sphygmomanometer and cannula for BP measurement and even to question and rethink the continued use of the BP "Gold standard" for diagnosis. This is not only supported by the popularity of these techniques amongst the general public but also the inbuilt blind faith in the technique amongst physicians. However, the large number of papers being published since several decades have finally given some impetus for research and development of new techniques, aiming at better accuracy and reliability and preferably also aimed at noninvasiveness for ease of use. On the other hand, this impetus has also given an opportunity for some of the engineering enthusiasts and researchers of the digital world to just impart that technology to develop modernized versions of the sphygmomanometer, while at the same time claiming to satisfy the need for continuous, ambulatory and outside the hospital measurement needs. Some of the proponents of such ambulatory and continuous monitoring devices also claim it to be an improvement of the sphygmomanometry itself! Unfortunately, all those modern digitized devises still suffer from the basic deficiencies of the technique of sphygmomanometry. In this author's view, such misapplication of modern digital technology without considering the fact that it could lead to serious consequences should not be ignored! Further, it should not be allowed to circumvent and hinder the development of alternative and improved techniques of measurement, if possible. Philip Lewis (2019) has described the details of the modern digital oscillometric technique and exposed its drawback of unique problems attributable to certain category of patients. Hence he suggested setting up treatment protocols based on the category of patients.

There are several noninvasive techniques which are being developed with the main idea of eliminating the cuff, simplifying and automating the measurement so that it can have the benefits of ambulatory and out of hospital application. Most of those werable type devices originate from the connection between blood pressure and arterial compliance or stiffness. They essentially employ the functional relationship developed by Moen-Korteweg & Bramwell-Hill (1922) between BP, arterial compliance, pulse wave velocity and arterial elasticity. Josep Carós (2011) developed a nonocclusive, noninvasive technique based on the measurement of Pulse Wave Velocity (PWV). His essential motivation was for replacing the cumbersome occlusive technique, which is not suitable for continuous, ambulatory measurement with a noninvasive, nonocclusive technique using Photo Plethysmography (PPG). Jayaraj Joseph et al (2018) have developed a wearable device for evaluation of pulse pressure based on local measurement of pulse wave velocity and arterial diameter.

However, PPG techniques based on measurement of pulse wave velocity has the drawback that they can only yield pulse pressure. To obtain BP, a knowledge of either SBP or DBP is required, which needs to be determined by some other means. Hence the PPG device need to be calibrated initially using simultaneous measurement of BP with Sphygmomanometry or Cannula. Both of those techniques are already being questioned for their serious deficiency concerning accuracy. This means that there is no basic standard or method which can be used for calibration. Hence the basic drawback of lack of a good fundamental standard for Blood Pressure measurement still remains. There is plenty of research being carried out using AI, ML and cloud computing for coming up with correlations or transfer functions between BP & PPG wave forms. This has led to some techniques either purely based on the use of such transfer functions or correlations and some also augmenting the application accuracy with individual or personalized calibration. The calibration is done on a large sample and also on a personalized basis intermittently. Both methods have their own deficiencies. Large sample alone is not sufficient to represent good and repeatable correlation between PPG and BP waveforms in all cases and particularly with patients having various comorbidities. Similarly personalized calibration might not also be repeatable always. This is because the fundamental issue of dependency of BP and PPG wave forms on anatomy, physiology and neuromechanics cannot be eliminated. These deficiencies are being attempted to be addressed in the present day by the progress in AI and ML technologies. They are expected to yield good functional relationships or correlations between the characteristics of PPG & BP wave forms. However such functional relationships again are statistical in nature and depend on how they were derived, what aspects of waveforms were modeled, what parameters, what type and how many samples were used, etc. Hence, these techniques are also not free from the important basic problems discussed below. Mohamed Elgandi et al (2019) have published an excellent review and analysis of the various types of wearable devices being developed based on PPG. The authors in that paper have clearly demarcated the problems as belonging to two classes. They identified that both types of problems are attributable to lack of a clear understanding, formulation and design of practical solutions to the issues involved in cardiac wave morphology arising from propagational and physiological characteristics. Essentially it boils down to the fundamental fact that each human is not only different than the other but also different from him/herself at different times. The use of modern day digital technologies involving cloud computing, AI & machine learning, which are being used could perhaps become useful in overcoming those problems only to a limited extent. Hence the need for well defined, large scale testing of various groups of people, development of good calibration techniques, standards and useful, openly available databases along with personalized methods of application whenever needed should become the basis for advancement of R&D for the success of wearable PPG devices for improving BP measurement. One should still note that this could only be an improvement over the present status but not a total solution, which appears to be still elusive!

Padwal Raj et al (2019) have estimated that amongst 1.4 billion persons classified as hypertensive about 84 million classifications are questionable. This leads to not only unnecessary medication to healthy persons but lack of treatment of those who have genuine BP issues. Hence they have established a collaborative group to promote not only accurate assessment and diagnosis of BP but also development of protocols for validation and standards for the measurement devices. This group consists of medical professionals, researchers, industrialists and even the general public to assist in achieving the ombudsman type objectives of the group. This author not only supports the objectives of such groups but also wishes success to such groups for the wellbeing of society. In fact, such organizations are required not only in the field of medicine but in many other areas also. Such need exists because any measurement like pressure in this case need to be either measured directly, or indirectly by sensing some other related physical parameter. Direct measurement of pressure whether invasive or noninvasive as with Cannula or sphygmomanometry have problems arising from various types of measurement inaccuracies caused by various factors in addition to correlation issues as in sphygmomanometry. In indirect techniques, determining the exact transfer function between the quantity to be measured and the sensed signal introduces not only the problems in determining the correct parameters and relationship defining the transfer function but also the usual errors in acquiring the signal itself. Hence in indirect measurements like PPG, as explained below more than all other inaccuracies, the application of Bramwell-Hill equation to measure pressure in human beings becomes a serious issue and need to be considered carefully.

1) Moen-Korteweg and Bramwell-Hill equations given below although claimed to be applicable to biological systems, such application is highly questionable.

Moens-Korteweg Equation, $v_p = \sqrt{\frac{E.h}{2.r.\rho}}$ …. (1)

where, v_p = pulse wave velocity, E = elastic modulus of the artery, h = arterial wall thickness, r = radius of the artery, ρ = blood density.

Bramwell-Hill Equation, $v_p = \sqrt{\frac{V.dP}{\rho.dV}}$ …. (2)

where, V = volume per unit length, P = Pressure.

The equations were initially developed (see Arris Tijjselling, 2012) for understanding fluid structure interaction and acoustic wave propagation in idealized isotropic, circular elastic tubes and not for living human arteries. The equations do not even contain any parameters characteristic of biological tissues or matter.

2) The concept of elasticity and plasticity was initially developed for nonliving matter, which can even assume a dynamic state when subjected to dynamic forces. The elastic modulus is not constant for human arterial passages. It varies both spatially and temporally depending on anatomy, physiology and neuromechanics. Nonliving matter cannot grow or evolve and hence can be described by fundamental laws of physics, while biological matter need not obey the fundamental laws of physics.
3) The human cardiovascular piping does not just consist of simple circular tubing but has a complex geometry. Its geometry is not homogeneous and the material properties including the elastic modulus could vary spatially and also temporally over a wide range of time scales. The short time scale dependence arises from physiology and neuromechanics and the long time scale dependence from anatomy. Hence the application of Moen-Koteweg & Bramwel-Hill equation which was originally conceived for mechanical tubing cannot be blindly extended to arterial systems by ignoring the large associated errors.
4) Characterization of the elastic behavior of nonliving matter by measurement & assigning elastic moduli is itself difficult when one deals with simple metallic substances. In addition, the elastic properties depend on the shape of the material also. When dealing with alloys, plastics, composites or other materials with complex composition and microstructure, the problem becomes even more difficult. Hence one can only imagine, how complex it is to understand the elastic behavior of living matter and then characterize it by assigning some definite properties. Such properties are transient in nature and do not follow any physical laws. Although techniques using AFM (Atomic Force Microscopy), SAM (Scanning Acoustic Microscopy) etc. have been developed to measure the elastic moduli of the biological materials like elastin, collagen, etc. present in arterial tissues, those techniques are mostly applied on tissue samples extracted from biopsies and not in vivo and hence the accuracy of using those values in the equation is questionable. One should also note that such elastic properties of individual proteins do not represent the behavior of an arterial tissue in a local or regional or systemic scale. The overall elastic behavior depends on the layout and the nature of bonding between such biological materials. One should also note that the material and its properties are continuously changing in living beings depending on the physiological & neuromechanical state.
5) The discovery of Piezo1 & Piezo2 mechano receptor genes externally on the cells of the skin as well as internally in arterial walls by Nobel Laureate Ardem Patapoutian (2022) has exposed clearly the micro mechanism of blood pressure regulation inside the artery and the tissue elasticity regulation outside the artery depending on the external stimuli sensed by the human body. It has clearly brought out the dynamic nature of blood pressure variation/regulation based on the internal arterial stimuli as well as the bioimpedance regulation of the tissue around the arteries inside the arm to external stimuli, whether it be through the cuff or other means. One should note that even the placement of sensor or transmission of an acoustic wave through the human tissue could arouse a sensory - regulatory response. Such response could result in altering the blood flow and pressure. Further such response is highly localized and hence cannot be defined to act in a predictable manner for defining the elastic behavior of the human tissue. Hence this throws a big wrench to defining the elastic behavior of human tissue by a constant or definable variation of elastic moduli and consequently to the application of Bramwell-Hill equation for estimating blood pressure.

Even if one were to come up with some measurement techniques, quantifying the uncertainties arising from the above problems is extremely difficult. Hence, the question reduces to the simple fact, whether one can overlook (as in the case of the present day BP measurement techniques themselves) the fundamental questions arising from the simple transplantation of techniques used for nonliving systems to biological systems. Particularly, extension of engineering knowledge to biological systems, when it comes to extending the laws of physics need to be considered with care, caution and concern.

4. CONCLUSION

1) The paper has exposed the serious deficiencies of the present day techniques used for measurement of blood pressure, particularly from a fluid dynamics view point.
2) As a consequence the paper has questioned the use of the "Gold Standard" used for its diagnosis.
3) It has also warned about the misapplication of modern day digital technology in the guise of improving the present day techniques as futile.
4) It has further raised serious questions concerning the transplantation of modern day engineering sensing and instrumentation techniques to tonometry, PTT, PPG, etc. for measurement of blood pressure from optical/acoustic signals in human beings, whose correlation depends on anatomy, physiology and neuomechanics!
5) To summarize, all of this leads to a basic and fundamental question whether Doctors can measure Blood Pressure and use it for reliably diagnosing human health?

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