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REVIEW ARTICLE

EXPLORING MEASUREMENT METHODS OF THE ARTERIAL PULSE

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ABSTRACT

Study of pulse-based diagnostic techniques is gaining popularity because of its importance in alternative medicine (Ayurveda, Unani, Traditional Chinese Medicine, etc.), increasingly being used in several countries worldwide. In Ayurveda, it is considered that imbalance in the *tridoshas* gives rise to the diseased state of the individual. Pulse-based diagnosis (*NadiPariksha* in Ayurveda) is a quick and simple technique where the Ayurvedic doctor (*vaidya*) gathers the information of the health condition by placing three fingers (index, middle and ring) on the wrist of the individual. Efforts are now being made to standardize the protocol for research in the Ayurvedic pulse-based diagnostic approach (over the last decade) by using instrumentation for acquisition and complex statistical analysis tools for the knowledge discovery process. The main aim of this review is to provide an overview of the data acquisition techniques used for Ayurvedic wrist-pulse based diagnosis. These contents are mainly extracted from the published work from approximately 50 journal and conference articles.

Keywords - Ayurveda, tridosha, pulse acquisition, sensor, pulse waveform.

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1. INTRODUCTION

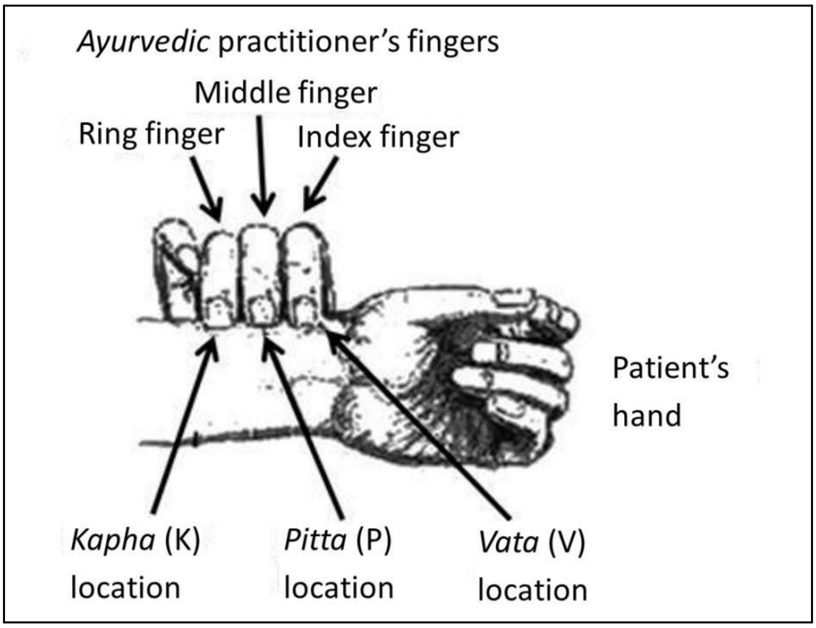
Ayurveda is one of the oldest forms of medicine and has been prevalent for over 5000 years. The verbal knowledge of Ayurveda passed on from generation to generation before the written texts could be available. At the time of 1500 B.C., Atreya (school of physicians) and Dhanvantari (school of surgeons) were the two schools teaching Ayurveda. Charak and Sushrut re-organised the Ayurvedic texts (including CharakSamhita, SushrutSamhita and AshtanghaHridayaSamhita) and their works are still available today (the texts are believed to be over 1200 years old).[1-3]

From the period of Sarngadharasamhita (13th Cent AD), *Nadipariksha* gets detailed description and then one can see descriptions in other texts such as Bhavaprakasha(15th Century AD), Yogaratnakara (16th AD) and so on. There are also many books recently published, written with the base of traditional text and own experience such as by Dr. Vasant Lad[4] and Dr. Upadhyaya.[5]

Ayurveda uses three measurement techniques to gather the above information namely *darshana* (observation), *sparshana* (touch) and *prashna* (questioning).[4]

In *sparshana*(touch) technique, the pulse on wrist (generally known as '*nadi*' in Ayurveda) discloses enormous information depending on its rate, rhythm, movement, force, tension and volume, consistency of the vessel wall and temperature.[4] Wrist pulse-based diagnosis, known as *NadiPariksha* in Ayurveda is one of the oldest forms/techniques for diagnosis. The technique of pulse-based diagnosis is shown in Figure 1 where the index, middle and ring finger, placed distally, medially and proximally to the heart are used to sense the *vata, pitta* and *kaphadoshas*respectively.It helps in the identification of the constitution at birth (*prakruti*) of the person, which forms the basis of the healing process. Knowledge of the current situation (*vikruti*) enables to identify the illness, considering the difference between *prakruti* and *vikruti*. It also tracks the psychosomatic or conflicting nature between the mind and body and helps in the analysis of the *tridoshas*.[4]

Figure 1. The traditional methodology of the pulse-based diagnosis. The Ayurvedic practitioner "feels" the pulse on the patient's hand to understand the imbalance in body. [4]

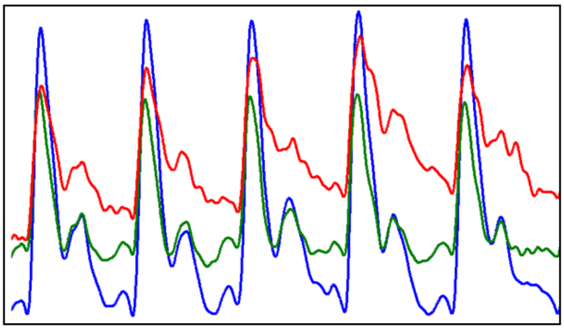


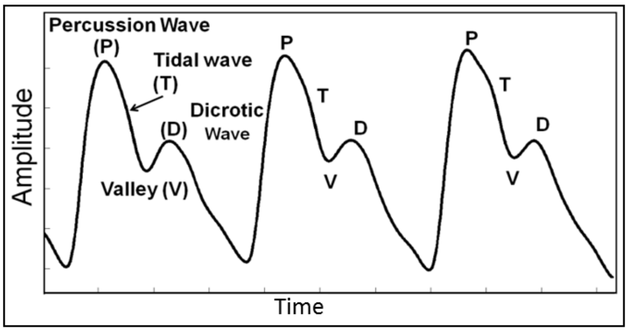
Pulse in modern medicine

Pulse assessment has its importance even in modern medicine. It is used as a primary diagnostic tool for examination of a person's heart rate and blood pressure parameters. The pulse by definition is the rhythmic beating of the arteries, caused by the recurrent contractions of the heart. Variations in pulse is considered as key diagnosis in heart conditions such as tachycardia, bradycardia, arrhythmia's etc.[6]

The arterial pulse is formed due to swelling (distension) of the arteries and the contraction which results due to the elasticity of arterial wall.[7] The contraction of the heart determines the frequency and rhythm of the pulse. The tension between the arteries and duration of the pulse depends on the elasticity and peripheral resistance.[7] A typical pulse waveform consisting of three beats is shown in Figure 2(b). The arterial pulse waveform typically consists of four areas namely the percussion wave (P), tidal wave (T), dicrotic notch (V) and dicrotic wave (D).

Figure 2. (a) Three waveforms obtained from the three sensors. (b) A typical pulse waveform with PTVD nature.


(a)



(b)

Percussion wave is the ascending portion of the graph formed during the systolic phase of the cardiac cycle. This P wave is caused from left ventricular ejection; followed by the tidal wave, which is a reflected wave. The dicrotic notch is a small downward deflection in the pulse contour occurring because of the closure of the semilunar valves, detecting the end of the systolic phase in the cardiac cycle in some instances. The wave trailing behind the notch is the dicrotic wave (recoil wave), formed because of the reflected impulse of closure of the aortic valves.General features which typically preside over the arterial pulse waveform are stoke volume, cardiac output, peripheral resistance, mean arterial pressure and arterial stiffness.

Need for scientific work on pulse-based methodology

Statistics has proven that approximately one third of the population in developing countries lack access to essential medicines. Thus, combining traditional medicine with conventional modern medicine could help provide better and safer facilities.[8] Regional language books and booklets on pulse have been published all over India based on personal experiences. One of the major drawbacks in the pulse-based diagnosis is that it is subjective and depends on the Ayurvedic doctor (*vaidya*) examining the patient. Also, the pulse waveforms vary from person to person, time of the day of obtaining the pulse, posture, timing and amount of food consumed by the individual. The lack of an official protocol for its standardization has caused a need for scientific recognition for Ayurveda.

Flow of the paper

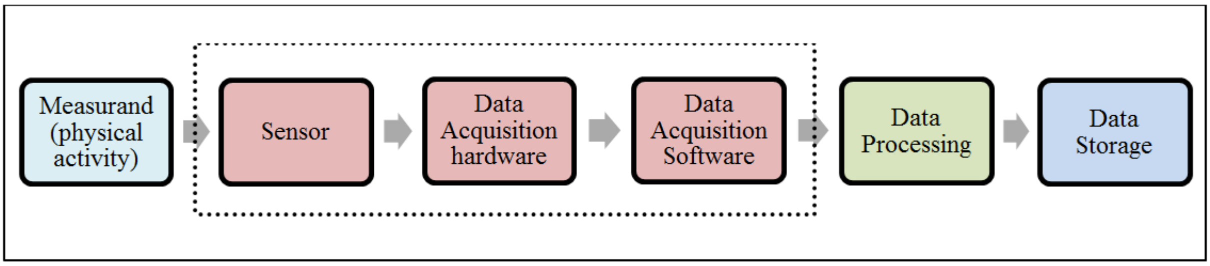
With increased awareness, many people are now looking at alternative medicinal techniques as the primary healthcare option. Research across continents has been conducted for improving the pulse acquisition and assessment systems. Different diseases or conditions cause variations in the typically obtained P-T-V-D waveform (refer to Figure 2(b)), which can be analysed by appropriate sensing, feature extraction, pattern recognition i.e. proper instrumentation. Pressure sensors are most widely used for pulse-based diagnosis and advanced research is being conducted for improving the sensing and instrumentation for the wrist pulse-based diagnosis.

The paper consists of aspects concerned with the radial pulse only. This paper is the first of a two part review where this paper includes varieties of sensors used in the radial pulse acquisition hardware along with a future work for incorporating other upcoming sensor technologies in the area. The second review includes the feature extraction techniques used for pattern recognition of the radial pulse and variations of the pulse patterns due to the onset of numerous physiological and pathological conditions with allied future work in the area.

2. PULSE ACQUISITION, PROCESSING AND STORAGE

Data acquisition is the first block in any data mining process. It is a measuring system of electrical or physical occurrences typically consisting of sensors, a measurement hardware system (DAQ) and computer with appropriate DAQ programmable software. PC-based DAQ systems provide a more cost-effective and flexible measurement solution. Processing of the data is required before analysis since it is obtained in the raw form and the steps of acquisition process are shown in Figure 3. Prior works of pulse acquisition and storage are discussed in this section.

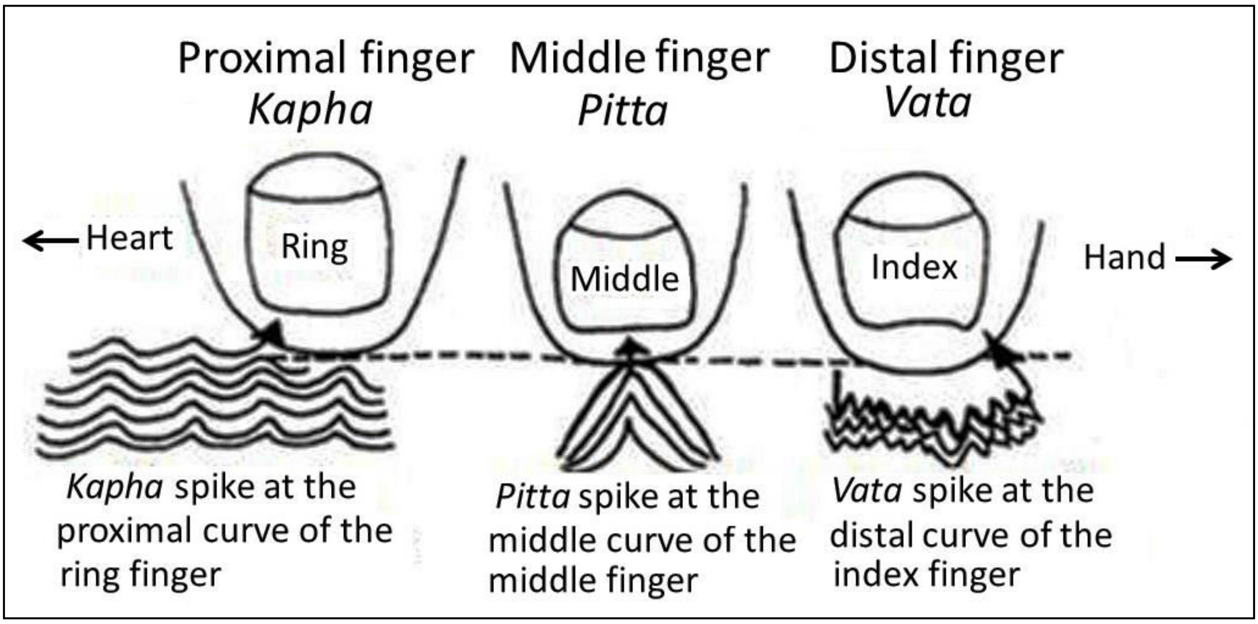
Figure 3. Typical steps in a data acquisition process.



The physical activity in this paper is the pressure variations on wrist (location shown in Figure 1) also termed as the pulse or *nadi*. According to Ayurveda, the flow of energy (or consciousness) is noticeable in the pulse through an individual's constitution. The flow of energy passes through the tissues, blood vessels etc. (till the cellular level) and facilitates the Ayurvedic practitioner to sense the blood flow.[9] Further, the symptoms of disease are always related to "imbalance" of the *doshas*, which can be determined by feeling the patient's *nadi*. The *nadi* has been chosen as the site to read the pulse because it is the most convenient to read and is the most readily available than other pulse sites.

The imbalance in body is governed through three *doshas* :*vata* (V), *pitta* (P) and *kapha* (K) combined as *tridoshas* (VPK). *Vatadosha*is considered as the indicator of energy of movement, *pittadosha*of digestion and metabolism and *kaphadosha*of structure and lubrication. The typical characteristics of VPK are displayed in Figure 4.

Figure 4. The position of the fingers to procure the tridoshas[4] and typical characteristic patterns of the pulse at locations of *vata, pitta and kapha*.



According to the traditional literature, the *vatadosha*is usually thin and weak. Its common patterns are represented by the *sarpa* (cobra) *gati*, *jalauka* (leech) *gati*, *krumi* (worm) *gati*, etc. The *pittadosha*is forceful, strong, prominent and has high amplitude. Its common patterns are represented by the *manduka* (frog) *gati*, *tittiraka* (partridge) *gati*, *kaka* (crow) *gati*, *lavaka* (common quail) *gati*, etc. The *kaphadosha*is deep, wavy, broad and slow. Its common patterns are represented by the *hamsa* (swan) *gati*, *kamala* (lotus) *gati*, *hasti* (elephant) *gati*, etc. The *padma* (lotus) *nadi* reflects a perfect health condition.[4]

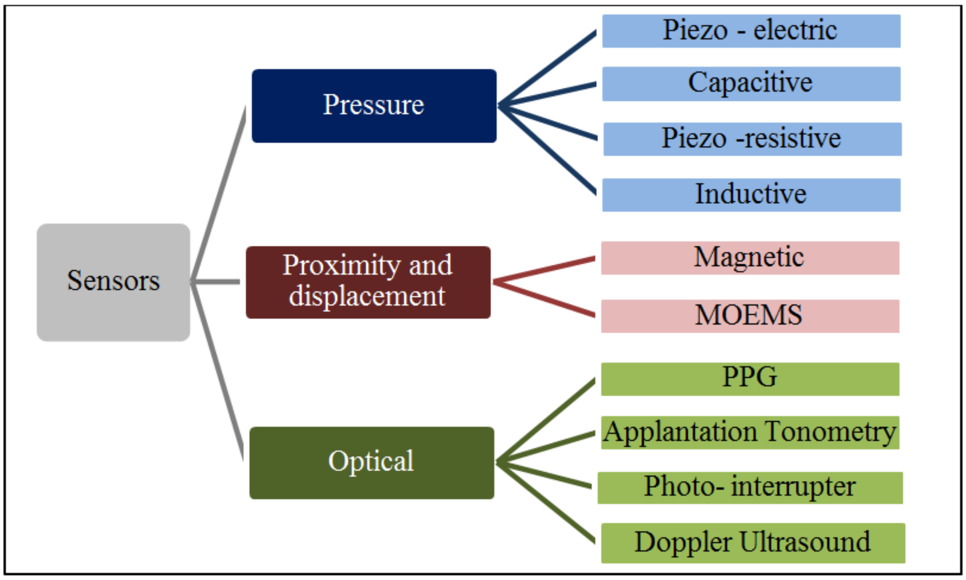
2.1. Pulse Acquisition

A transducer is a device which converts the energy from one form to another compared to a sensor which converts into an electrical output.[10] For the purpose of this paper, note that the term sensor and transducer are used interchangeably. Accuracy, precision, range, calibration, environmental conditions, resolution, cost and repeatability are some of the essential criteria in choosing a sensor for an application.

The beginnings of the acquisition of the non-invasive pulse can be traced to the year 1555, when the physician Struś had proposed that the arterial pulse possesses a waveform.[11] Although the instrumentation he used was simple, he suggested that changes in the arterial pulse shape and strength might be related to disease conditions. Until now, there have been various acoustic, photoelectric, and mechanical sensors proposed for the acquisition of the pulse signals. Generally, it has been observed that pressure sensors are more widely used for pulse-based analysis. However, newer research has also incorporated the use of charge coupled device (CCD) and Hall sensor (magnetic).[12]

The classification of most sensors (in recent studies) is summarized in Figure 5 and is explained in the subsequent subsections. The choice of sensors varies with application, design, performance and cost.

Figure 5. Types of sensors used for acquisition of the pulse.



2.2. Pressure Sensors

A pressure sensor converts the applied pressure to a measurable electrical output signal and is commonly used to measure the pressure in fluids and gases.[10] Most of the pressure sensors have the mechanical element as piston, bourdon tube, diaphragm, bellows, or strain gauge. Among the literature obtained for the sensors used in biomedical applications, diaphragm and strain gauge are popular. Important varieties in the pressure sensor technologies are as given below.

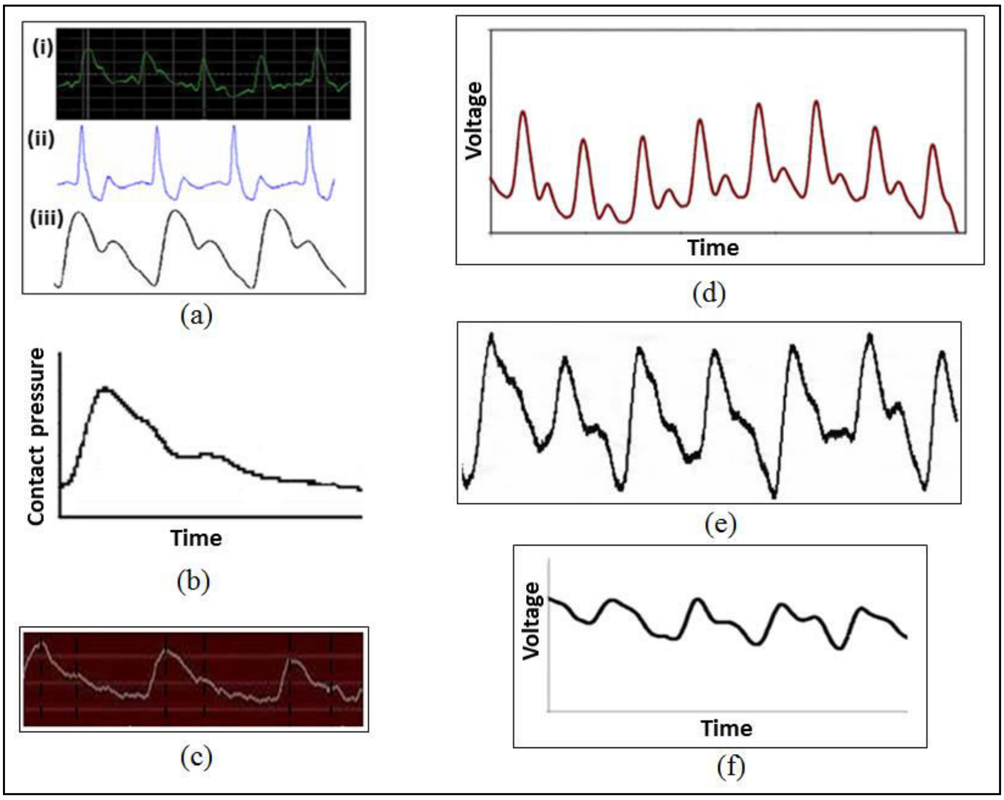
2.2.1. Piezoelectric Pressure Sensor

Piezoelectric effect occurs when mechanical stress in certain non-conducting materials induces electricity. Quartz is the most commonly used piezoelectric crystal material in applications. A vital property of the piezoelectric pressure sensor is that it is dynamic in nature i.e. it detects an output only with varying inputs and hence efficient at times of variation in pressure. Since the human pulse pressure is dynamic in nature, piezoelectric sensors have been used extensively in pulse-based diagnosis.[10] A pressure sensor coated with PVDF material has been used to obtain the pulse because of its non-reactivity, unusually large dipole moment, crystalline and dynamic nature of the coated material.[13] In [14], the sensor identifies the periodic changes in the diameter of the arterial wall and combined with signal processing techniques (integrator), yields the pulse pressure waveform. Sample pulse waveforms from one of the VPK locations are displayed in Figure 6(a). Note that the PTVD (refer Figure 2(b)) nature of the pulse has been captured in all the three systems.[13-15]

2.2.2. Capacitive Pressure Sensor

In capacitive pressure sensor, the capacitance changes due to variations in the distance between the surfaces; indicating proportional changes in the target.[16]Diaphragm generally forms one end of the capacitor and the variations measured are characteristically of the order of picofarads.[16] Some of the advantages are insensitivity to material changes, high resolution and cost effectiveness. Due to the ease in miniaturization of the sensor, it has applications in implantable sensing device. However, attempts are being made to use the sensor non-invasively in applications. Capacitive tactile array sensors are alsoused for obtaining the wrist pulse waveforms.[17]

Figure 6. (a) Sample pulse waveforms recorded using piezoelectric pressure sensor for (i), (ii), (iii) in [13], [14] and [15] respectively. (b) A piezoresistive pressure sensor output for a small segment (4.25-4.5 mm).[18] (c) Radial arterial pulse waveform obtained by using Hall sensor.[21] (d) GMR sensor output.[26] (e) PPG obtained pulse waveform.[25] (f) Radial pulse using photo-interrupter sensor after filtering.[35]



2.2.3. Piezoresistive Pressure Sensor

Piezoresistive pressure sensors detect changes when variations exist in the electrical resistivity of a semiconductor or metal when mechanical strain is applied. It is generally made up of silicon substrate as the sensing material. Some of the advantages of piezoresistive pressure sensors are low fabrication cost and high sensitivity to variations in pressure levels. It is used in biomedical applications such as blood pressure measurement systems and efforts are being made to use it for pulse-based diagnosis. Apiezoresistive sensor is combined with the strain gauge as the acquisition tool followed by signal conditioning circuits but was not found effective at times of excessive contact pressure(as shown in Figure 6(b)).[18]

2.2.4. Electromagnetic or Inductive Pressure Sensor

Changes in the electromagnetic pressure sensor occur because of variations in the relative permeability of the ferromagnetic core, modifying the inductance. Small size, high sensitivity, low temperature hysteresis and low power consumption are some of its advantages.[19] The disadvantage is requirement of AC excitation of the coils. Linear variable differential transformer (LVDT) and hall effect sensor are some of the senor examples.[20] In [21], a device using Hall sensor was utilized which sensed the changes in periodic movement due to changes in the magnetic field (Figure 6(c)) but further analysis was required to check the reliability of the device.

2.3. Proximity and Displacement Sensor

Proximity and displacement sensors are non-contact sensors having biomedical applications, especially in robotics. Proximity sensors can identify the presence of objects within a certain range without physical contact generally using electromagnetic field.[22] Displacement sensors measure the change of position of an object and gives an electrical output.[23]The main benefits of proximity and displacement sensors are high accuracy, easy maintenance, long life span, good repeatability and reliability. The outputs obtained from these sensors do not require amplification that avoidsthe associated artefacts.

2.3.1. Magnetic Sensor

A magnetic sensor is a proximity sensor that uses a combination of a reed switch and magnet to detect the presence of magnetic field. [24] This type of sensor application is not very widely used in pulse-based diagnosis but research is carried out for its incorporation in the field. The key importance of this sensor is its high sensitivity and accuracy.[25] A technique of magnetic signature to detect the arterial pulse signal has been utilized where a Giant Magnetic Resonance (GMR) (as shown in Figure 6(d)) sensor output yielded a prominent pulse signal which was concurrent to the blood volume; linking the output with arterial stiffness.[26]

2.3.2. MOEMS Sensor

An addition of optical components into a micro-electro-mechanical system (MEMS) device is termed as micro-opto-electro-mechanical systems (MOEMS). The sensors are used as optical switches andfabricated using micro-optics and standard micromachining technologies.[27]The advantages are low cost and extremely small size. An MOEMS system coupled with charge coupled device (CCD) sensor was used for TCMandwas proven efficient and highly sensitive in detecting the arterial deviations caused due to blood pressure changes.[12]

2.4. Optical Sensors

Optical sensors record objects by means of energy or particles transmitted and reflected by the objects. A fibre optic sensor can be used interchangeably depending on the applications as either in the sensing or in the electronics to process the signal. Some of the advantages of the fibre are small size, sensor multiplexing, effective even without electrical power, high temperature applications, resistant to magnetic interference, etc. Plethysmography, applantationtonometry and doppler ultrasound techniques are some of the optical sensor techniques in the biomedical industry.

2.4.1. Plethysmography

Plethysmography detects the volume changes of an organ. Photoplethysmography (PPG) is optically obtained and is incorporated in pulse oximeters to find the oxygen saturation and pulse waveform.[28] It has several biomedical applications and extensively used for vascular assessment and autonomic function. Some of the advantages are low cost, simple operation and non-invasive nature.[29]Figure 6(e) is an example showing the PPG waveform of the pulse signal. It is generally used as a finger PPG method (not radial pulse) and is useful in finding several properties such as arterial stiffness[30], compliance[31], pulse wave velocity.[32] However, the disadvantage is that it is extremely sensitive to motion artifact.[9]

2.4.2. Applantation Tonometry

Applantation tonometry is a measure of pressure which was initially used for the measurement of the intra-ocular pressure. Carotid tonometric sensor is used for pulse wave analysis for the arterial pulse which is useful in the early detection of cardiovascular and cerebrovascular disorders.[33] It has been used to monitor the pulse contour of critically ill patients but it was not found to be very effective.[34]

2.4.3. Photo Interrupter Sensor

Photo Interrupter sensor contains an opto-electronic subsystem composed of transmitter (IR LED) and a receiver (photo sensor). They are incorporated as one unit. When the digital logic is one, the sensor generates the output.An array of photo interrupter sensors were used in [35], and had accurate results for elderly patients and active people because of the system being robust (Figure 6(f)).

2.4.4. Doppler Ultrasound and Echo Tracking

Doppler ultrasound is a technique which uses the reflected sound waves to derive the flow of blood in the blood vessels.[36] Doppler ultrasound has majority applications in the imaging of soft tissues. It has been successful in finding the disease through the velocity – time waveform, which defines the vascular properties of the arterial segments.[37] According to the study in [38], the Doppler ultrasound device is slightly more effective in the measurement of the pulse compared to the pressure sensor where the device had an accuracy of 86%.

2.5. Comparison of sensors

Choosing an appropriate sensor reduces the cost without compromising the features. As observed from Table 1, because features are comparable and apt to pulse-based diagnosis, pressure sensors are most frequently used.

Table 1. Comparison of sensors utilized for pulse-based acquisition.

Sensors / Features	Pressure	Proximity and Displacement	Optical

Cost effective	✓	✓	Sometimes
Light weight	✓	Sometimes	✓
Non-invasive	✓	✓	✓
Simple operation	✓	✓	✓
Accuracy	✓	✓	✓
Electrical Safety	✓	✓	✓
Wide Dynamic Range	✓	Sometimes	✓
Reliability	✓	✓	✓
Variations in Pressure	✓	Sometimes	Sometimes
High Resolution	✓	Sometimes	✓
Electromagnetic Interference Sensitivity	✓	×	✓
Insensitivity to material changes	✓	×	Sometimes

3. DISCUSSION

The knowledge of Ayurveda is holistic, varies in treatment for every individual and is gaining importance for cure.[39] Several attempts are being made to correlate the basic fundamentals of Ayurveda (such as *tridoshas*, *trigunas*, *panchamahabhoota*) with the scientific world.Ayurvedic principles have been relatedto other scientific theories such asquantum logic[40], Newtonian laws[41]and systems theory.[42, 43]

Research has been extensively carried out for the correlation and quantification of another pulse diagnostic technique – TCM.From the 1950's, there havebeen several publications with an aim to provide a scientific base for its validation in terms of modern medicine. One of the most popular method is to quantify eight elementsnamely depth, rate, regularity, width, length, smoothness, stiffness, and strengthobtained from each pulse to the standard arterial pulse waveform.[44]Similar efforts could be carried out which can validate the Ayurvedic principles and help in its scientific recognition. One of the biggest challenge is, according to the Ayurvedicprinciples, no two people are alike and therefore there are variations in the manner of treatment. Hence, the laboratory experimental methods have not been successful in meeting the standards for clinical trials in Ayurveda. New endeavours are being carried out by AYUSH (Ayurveda, Yoga & Naturopathy, Unani, Siddha & Homoeopathy) such as quality control and standardization of manufacturing units across the country, study of classical Ayurvedic medicine based on western parameters, creating a new protocol for medicines etc. in pursuit to reduce the variation and regulate Ayurveda.[39]

3.1. Future Work

There is a lot of ambiguity regarding the Ayurvedic pulse and more research is required to give it a scientific base. Direct correlations of the radial pulse waveform with Ayurveda in terms of modern medicine or vice versa is required for itsscientific recognition in India and abroad.

3.1.1. Validating Concepts

Various researches were conducted to determine the pattern of the pulse waveform for changes in the auditory perception.[45] Although the studies were not entirely conclusive, further research could bring new perspective in this area.

There are seven levels of the pulse on wrist for each of the *tridosha* location (*vata*, *pitta* and *kapha*), and for every combination of a level and location, a different disease/condition could be identified.[4] However, when the available sensors are used, the individual level of the pulse cannot be identified; thus providing onlyan overview of the disease at the first level (*vikruti*) of the pulse. Hence, a possibility could be, to quantify the variations in the pulse contour of the seven levels of the pulse individually to different disorders.

According to Ayurveda, at different times of the day, month and year, different *doshas* are prominent which affect the balanced nature. Any change in *kala* (time) generates *ama*, causing changes in the concerned *doshas*and therefore, in the *dhatus*. Research is being carried out to correlate *kala*and *nadipariksha.*[46]However, more studies are required to compute the modifications in the pulse pattern owing to these climatic and environmental changes.

In addition, there is no scientific evidence from physics point of view, why pulse is sensed particularly on the right hand in males and left hand in females. There is no sufficient explanation for pulse signals on the same artery at three locations displaying a varied nature as shown in Figure 2(a).More research would prove beneficial in bridging the gap in modern medicine and Ayurvedic form of diagnosis.

3.1.2. Enhancing Data

Ayurvedic practitioners believe that the pulse is available at many minute locations on each fingertip. Though these locations (on each fingertip) will contain almost the same information, the practitioners are able to sense the differences with high concentration. Currently all systems are limited to just one sensor at V-P-K location (for each fingertip). It is a good approximation for beginning the research but to entirely mimic the Ayurvedic methodology, a data acquisition system is required to capture the pulse signals at many more locations. A tactile-sensing array could be used for this purpose, which is a coordinated group of touch sensors. It involves the detection and measurement of the spatial distribution of forces perpendicular to a predetermined sensory area, and the subsequent interpretation of the spatial information. When the tactile sensor is exposed to the wrist region (where the pulse is available), then it would help in acquiring the pulse signals from many locations.

One limitation in the data acquisition process is the outliers due to sudden movements of hand (or body), or other noise inducing factors. Also in few cases, data for a particular sensor (*dosha* location) is missing due to its negligible amplitude or an improper placement of the sensor on wrist. Currently, most of the systems do not handle these issues. A typical database also contains the pulse signals (time series or image format), the patient’s information and the doctor’s diagnosis. Thus, the database is a combination of various media – numeric (data), symbolic (gender, habits), text (doctor’s diagnosis) and images. For better results, all these data types must be handled efficiently.

4. CONCLUSION

The pulse-based assessment technique is non-invasive, simple to perform and cost effective. Using instrumentation for pulse acquisition and obtaining the P-T-V-D waveform is an effort to standardize the procedure of procuring the pulse. Considering criteria such as cost effectiveness, compactness, contact pressure, temperature, linearity, accuracy, repeatability, precision and connectivity enables the proper selection of pulse acquisition sensor. Computers for large-scale data handling with appropriate mathematical, statistical and logical tools have enabled suitable feature extraction and knowledge discovery for the diagnosis.

Comparing the Ayurvedic principles with modern medicine is an attempt to authenticate the traditional techniques in today's modern (or allopathic) medicine world. More studies based on the P-T-V-D waveform also could enable the incorporation of the system at households and hospitals; providing quick and accurate systems.

A synopsis of the different acquisition sensors has been provided. Pressure sensors are significantly usedin pulse-based diagnosis. Tactile sensors, which areused increasingly for touch-based applications, have a promising future in pulse-based diagnostic systems.

An ease in the process of the pulse acquisition and assessment has become an important cause for a large population in India and the worldto utilize this alternative technique as a method of primary healthcare. It has therefore become important for the proper standardization and instrumentation of the pulse acquisition. Attempts are now being made in this direction but it is essential to make the system cost effective and simple in usage for efficient patient care.

REFERENCES

1. World Health Organization. WHO Traditional Medicine Strategy: 2002-2005. Geneva; 2002. Available from : http://www.wpro.who.int/health_technology/book_who_traditional_medicine_strategy_2002_2005.pdf

2. DebasHT, Laxminarayan R, Straus SE. Complementary and Alternative Medicine. In: Jamison DT BJ, Measham AR, et al., editors. Disease control priorities in developing countries. 2nd ed. Washington (DC): World Bank; 2006.

3. Mishra L, Singh B, Dagenais S. Ayurveda: a historical perspective and principles of the traditional healthcare system in India. AlternTher Health Med 2001;7(2):36-42.

4. Lad VD. Secrets of the pulse. 1st Indian ed. New Delhi: MotilalBanarasidass; 1996.

5. Upadhyaya S. NadiVijnana : Ancient pulse science. Chaukhambha Sanskrit Pratishthan, Delhi, 1986.

6. Moran JF. Pulse. In: Walker HK, Hall WD, Hurst JW, editors. Clinical Methods: The history, physical, and laboratory examinations. 3rd ed. Boston:Butterworths;1990. pp. 98-100.

7. Thomas JC. The human pulse[Internet]. 1895: [cited November 2013]. Available from: http://chestofbooks.com/reference/Manual-Useful-Information/index.html#.UvySofm6zDk.

8. World Health Organization. How safe is traditional medicine? [Internet]. c2014. [updated 2005; cited 2013 November]. Available from: http://www.who.int/features/qa/20/en/index.html.

9. Trivedi B. Pulse Reading: The miraculous art & science of diagnosis [Internet]. SanDiego; [cited November 2013]. Available from: http://www.amritaveda.com/learning/articles/pulse_reading.asp

10. Clark JWJr, NeumanMR, Olson WH, Peura RA, Primiano FP Jr, Siedband MP, et.al. Medical Imstrumentation: Application and Design. 3rd ed. Delhi: Nice Printing Press; 2007.

11. Struś J. Sphygmicaear tis jam mille ducentosannosperitae et desiderataeLibri V.: A josephistruthioposnanience,medicorecensconscripti, Basel (As transcribed by A. Noordergraaf, University of Pennsylvania, Philadelphia, PA); 1555.

12. Palevicius P, Malinauskas K, Ragulskis M, Ostasevicius V, Dauksevicius R. Validation of noninvasive MOEMS-assisted measurement system based on CCD sensor for radial pulse analysis. Sensors 2013;13:5368-5380.

13. Mahesh S MM, Anandan T. Three radial artery pulse sensor design for Siddha based disease diagnosis. J SystCybernInf 2008:19-23.

14. Ghatak SS, Sur S. An inexpensive arterial pressure wave sensor and its application in different physiological condition [Internet]. 2006 [cited 2013 December]. Available from http://arxiv.org/abs/physics/0512071.

15. Joshi A, ChandranS,JayaramanVK, Kulkarni BD. A Novel PSWT-DTW approach for analyzing pseudo-periodic signals.IEEE Point of Healthcare Technologies 2013. p. 58-64.

16. Bicking RE. Fundamentals of pressure sensor technology [Internet].Sensormag; c2014. [cited 2013 November]. Available from: http://www.sensorsmag.com/sensors/pressure/fundamentals-pressure-sensor-technology-846.

17. Chung YF, Hu CS, Luo CH, Yeh CC. Temporal and spatial properties of arterial pulsation measurement using pressure sensor array. Evid Based Complement Alternat Med 2012.

18. Liu SH, Tyan CC. Quantitative analysis of sensor for pressure waveform measurement. BioMedical Engineering OnLine 2010;9(6).

19. Deji A, Khan S, Shobaki MMM, AlamAHMZ, Chebil J, Malik NA. Design of a differential sensor circuit for biomedical implant applications.AustJ Basic ApplSci 2012;6(9):1-9.

20. BakhoumEG, Cheng MHM. High-sensitivity inductive pressure sensor. IEEE Trans InstrumMeas 2011;60:2960-2966.

21. Nam DH, Lee WB, Hong YS, Lee SS. Measurement of spatial pulse wave velocity by using a clip-type pulsimeter equipped with a hall sensor and photoplethysmography. Sensors 2013;13:4714-4723.

22. Displacement and position sensors [Internet]. India: National Instruments Corporation ; c2014. [updated 2014; cited February 2014]. Available from: http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n21:11/fmid/3003/.

23. Ahmad H, Harun SW, Yang HZ, Yasin M. Fiber optic displacement sensors and their applications In: YasinDM, editor. Fiber Optic Sensors: InTech; 2012. p. 359-92

24. McGraw-Hill Dictionary of Scientific and Technical Terms. 6th ed. The McGraw-Hill Companies Inc; 2002.

25. Chung SC, Kwon JH, Lee B, Yi JH, Km HJ, Tack GR. Development of a magnetic-resonance-compatible photoplethysmograph amplifier for behavioral and emotional studies. Behav Res Methods 2008;40(1):342-6.

26. Jayashankar V, Joseph J. Magnetic sensor for non-invasive detection of blood pulse and estimation of arterial compliance. ConfProc IEEE Eng Med BiolSoc 2010.pp.170-5.

27. MEMS and Nanotechnology Exchange [Internet]. Virginia: CNRI; 2014 [cited January 2014]. Available from: https://www.mems-exchange.org/MEMS/what-is.html.

28. Gupta S, Singh M. PPG profile investigations for different fingers in a subject. International Journal of Computer Science and Communication 2011;2(2):377-9.

29. Allen J. Photoplethysmography and its application in clinical physiological measurement. Physiological Measurement 2007;28(3):R1-R39.

30. Langereis G. Photoplethysmography (PPG) system 2010. Available from: http://www.geertlangereis.nl/Electronics/PPGSensor/PPG%20Sensor%20System.pdf.

31. Raamat R, Jagomagi K, Talts J. Calibrated photoplethysmographic estimation of digital pulse volume and arterial compliance. ClinPhysiolFunct Imaging 2007;27:354-62.

32. Marcinkevics MG Z, AivarsJI, Erts R, ZehtabiAH.Relationship between arterial pressure and pulse wave velocity using photoplethysmography during the post-exercise recovery period.ActaUniversitatisLatviensisser Biology 2009;753:59-68.

33. Narimatsu K, Takatani S, Ohmori K. A multi-element carotid tonometry sensor for non-invasive measurement of pulse wave velocity. Front Med BiolEng 2001;11(1):45-58.

34. Compton F, Wittrock M, Schaefer JH, Zidek W, Tepel M, Scholze A. Noninvasive cardiac output determination using applanation tonometry-derived radial artery pulse contour analysis in critically ill patients. AnesthAnalg 2008;106(1):171-4.

35. Kagawa T, Kawamoto A, Nakajima N. Robust wrist-type wireless multiple photo-interrupter pulse sensor. International Journal Of Systems Applications, Engineering & Development 2012;6(5):325-32.

36. WebMD.com [Internet]. WebMD Medical Reference from Healthwise; c2005-2014 [updated 2012 November 29; cited 2013 November]. Available from: http://www.webmd.com/dvt/doppler-ultrasound.

37. Atkinson P, Wells PNT. Pulse-doppler ultrasound and its clinical application. Yale J Biol Med 1977;50:367-73.

38. Zhang D, Zhang L, Zhang D, Zheng Y. Wavelet based analysis of Doppler ultrasonic wrist-pulse signals. International Conference on BioMedical Engineering and Informatics 2008.pp.539-43.

39. Patel P [Speech] Ayurveda - A Journey From Scientific Foundation To Global Vision Published Reports of International Ayurveda Foundation: The International Ayurveda Foundation; 2005 [cited 2014 January]. Available from: http://iaf-ngo.org/published_reports.html.

40. Singh RH. Exploring quantum logic in ayurveda with special reference to Srotovijnana of Ayurveda.Ayu - An International Quarterly Journal of Research in Ayurveda 2009;30(4):360-8.

41. Iradier MAM. The left hand of chaos (Modern and Ancient Indian analysis) [Internet]. c2005. Available from:
http://empslocal.ex.ac.uk/people/staff/mrwatkin/isoc/iradier.pdf.

42. Hankey A. Ayurvedic physiology and etiology: Ayurveda Amritanaam. The Doshas and their functioning in terms of contemporary biology and physical chemistry. J Altern Complement Med 2001;7(5):567-74.

43. Joshi RR. A biostatistical approach to ayurveda: quantifying the Tridosha. J Altern Complement Med 2004;10(5):879-89.

44. Tang ACY. Review of Traditional Chinese Medicine pulse diagnosis quantification. In: Saad M, editor. Complementary therapies for the contemporary healthcare. Hong Kong: InTech; 2012. pp. 20.

45. Joshi P, Daruwala R. Objective Evaluation of radial pulse signal. Annual IEEE India Conference (INDICON) 2013. pp. 1-4.

46. ShashirekhaH.K, Sukuar B.S. NadiPariksha: An Interpretation of NadiPariksha With Reference to Kala. Punarnava - An International Peer Reviewed Ayurved Journal 2014;2(2).

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