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A comprehensive review on technological advancements for sensor-based Nadi Pariksha: An ancient Indian science for human health diagnosis

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A R T I C L E I N F O

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A B S T R A C T

Nadi Pariksha is a significant, rather symbolic term for Ayurveda. Ancient Ayurvedic literature has prominently stated its importance in the judgment of *Tridoshas* (*Vata*, *Pitta*, and *Kapha*) which are the base of ailment diagnosis and prediction. The knowledge about *Nadi Pariksha* is uncovered in various ancient Ayurvedic literature like Ravansamhita, Bhavprakash, *Nadi*vigyan by Kanad, Sharangdhar, and Yogratnakar. The various *Nadi* parameters are indicative of the diagnosis of diseases. These techniques were used as popular diagnostic tools in Indian culture from ancient days. Still, nowadays, these are not being used explicitly due to the lack of expertise, so it is necessary to establish their results once gained so that they can be used along with technical aspects in today's era. Ayurveda believes that all the elements of the Universe are present in any human body in minute, proportionate quantity, and the *Nadi* represents these elements, that is, *Vata*, *Pitta*, and *Kapha* (VPK). To facilitate the *Nadi Pariksha* using appropriate sensors may help the Ayurveda practitioners diagnose Prakriti and predict some diseases, making the *Nadi Pariksha* more reliable and faster.

This review paper lists, 2 books and 67 research papers, mostly from countries like India, China, Japan, Korea, etc., from various reputed databases. The review primarily concentrates on six research themes: sensors and devices used for Nadi signal acquisition, signal pre-processing methods, feature extraction methods, feature selection approaches, classification practices, diseases diagnosed, and results attained. The paper also reviews the challenges in implementing the automated Nadi Pariksha with technological aid, which is a necessity of this period and is a very vibrant research arena. Yet significant work remains to be done, like bridging the gaps between technical and commercial development, and the procedure standardization is also required.

1. Introduction

On any human body, the pulse could be felt and measured at various locations having various names like popliteal (behind the knee), temporal (forehead), posterior tibial (ankle), carotid (Neck), dorsalis pedis (instep), apical (heart), radial pulse (wrist), brachial (elbow), femoral (thigh). In Ayurveda, the radial pulse is called *Nadi* and has importance in disease diagnosis. A radial pulse wave represents the pressure of the blood vessels. Ayurveda is a hands-on, experimental, medicinal science. It has eight methods to examine the patient, examination of *nadi* (pulse), *mutra* (urine), *mukh* (face), *chakshu* (eyes), *jivha* (tongue), *vacha* (speech), *charma* (skin), and *mala* (stool). Pulse examination stood most important among them all. This art of examination is used by Ayurveda since ancient times. The expert Ayurvedic specialist will assess *vikruti*, *prakriti,* and *dosha* disorders, and other sensitive interpretations and even predict the disorder from the pulse. *Nadi Pariksha* is just a door to be opened to explore human body functions. Pulse is precise, evidence of all five elements of universe responsiveness pulsating through an individual's body constitutes. *Nadi* is a passage in the form of blood vessels in an individual's body which has many parameters. Ayurveda broadly uses three techniques to examine the patient: *darshana*, *sparshana,* and *prashna*. *Darshana* means pure observation done by the practitioner to draw some conclusion. It is what the perception stated by visual inspection. *Sparshna* is the physical experience of touch. The practitioner will feel the *nadi* and try to diagnose the *dosha*. In some patients, the *nadi* is difficult to feel and maybe is traceable only on one side. *Prashna* is asking questions. The Ayurveda practitioner generally asks questions about the symptoms and takes the medical history. Using these answers,

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the practitioner may conclude some points which could be matched with the above two techniques. Air (*Vayu*), fire (*agni*), ether *(akash*), earth (*prithvi*), and water (*jal*) are the five basic constituents, minutely present in any individual body as three fundamental *doshas* known as *Tridoshas*, *vata*, *pitta*, and *kapha* [1]. Fig. 1 shows the body constitution.

The fire *dosha* called *pitta* is manifested by Fire and Water elements together. The air *dosha* called *vata* is manifested by the Ether and Air elements. The Earth and Water elements together form a water-dominant *dosha* called *kapha*. These *vata, pitta,* and *kapha doshas* together are called *tridoshas* and lead to determining the individual composition and directing the working of the human body in normal conditions. If any kind of im*bala*nce occurred due to circumstances, then this disorder may lead to diseases. This shows that the *Doshas* in any human body are required to be *bal*anced to be in a healthy condition.

वातं पत्तिं कफं द्वन्द्वं त्रतियं सान्नपितिकम् ।

साध्या साध्यववकिं च सर्व नाडी प्रकाशयेत ।।

Shloka from YogRatnakar [2].

Meaning, *Nadi Pariksha*, when done accurately, helps to identify the *VPK* im*bala*nce and prognosis of diseases.

The rest of the paper is arranged in three sections. Section 2 describes the traditional method for *Nadi Pariksha*, its parameters, and its resemblance with the scientific parameters. Section 3 elaborates on four major components of the automated *Nadi Pariksha* model. Section 4 discusses the challenges and future direction of the work. Later challenges and conclusion are represented from this extensive survey.

2. Nadi Pariksha

Ayurveda Practitioners sense the *Nadi* below the thumb on the Wrist. The *nadi* parameters are important to diagnose any disease, the palpation of the *Nadi* talks about the presence of any *Tridoshas* in the Human body. Various parameters play important role in exploring *Tridoshas*. According to the secret of pulse [1] the parameters which can be considered important are *vega* (rate), *gati* (movement), *Bala* (force), *kathinya* (consistency of vessel wall), *Tala* (rhythm), *Akurti* (tension & volume), *Tapamana* (temperature). These parameters show significant variations when compared to *vata, pitta & kapha Doshas*. Table 1 shows these variations.

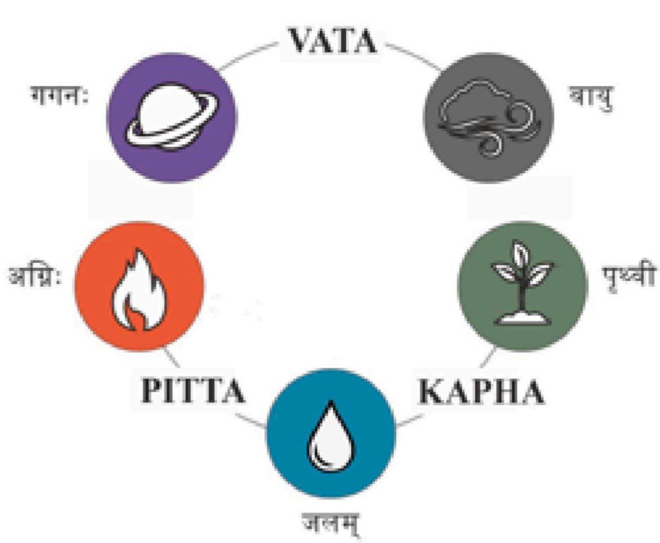

Fig. 1. Body constitution

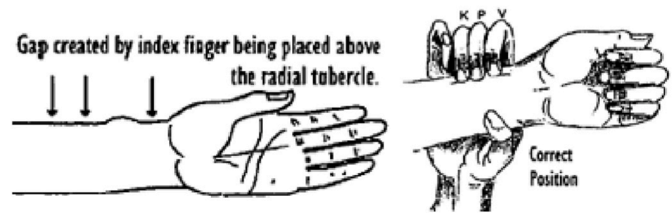

Fig. 2. *Nadi Pariksha* [1].

Table 1
Pulse Parameters as described in Ayurveda [1].

	Vata	Pitta	Kapha
Gati	*Snake*	*Frog*	*Swan*
Vega	80–95	70–80	50–60
Tala	Uneven	Even	Even
B ala	Low +	High +++	Average ++
Akurti	Low	High	Average
Tapamana	Cold	Hot	Warm To Cool
Kathinya	Rough, Hard	Elastic Flexible	Soft Thickening

2.1. Method followed to sense Nadi

It is written in the text that due to planetary action (change in sun & moon positions); *Nadi* palpates differently at various times of the day. For good results, *Nadi* is supposed to be checked in the morning, empty stomach, or 3 h after the meal, in restful condition. The best position considered is as the patient's hand should be slightly bent at the elbow and relaxed, then the practitioner should softly place three fingers on the skin near the wrist over the radial artery. First, the index finger must be placed near to thumb, next to it the middle finger, and next to the ring finger. According to the text, the index finger indicates the *Vata dosha*, the middle finger denotes the *Pitta dosha*, and the ring finger indicates the *Kapha dosha*. Experienced practitioners feel the *Nadi* and convert the feelings to appropriate disease or aggravated *dosha*. Fig. 2 shows how to hold the wrist of *Nadi Pariksha.*

2.2. Traditional parameters of Nadi and their resemblance with scientific parameters

The human heart is nothing but a pump and the pumping leads to the development of pressure in the arteries and the aorta. If this pressure (aorta) is recorded and plotted as a graph of pressure over time, a pressure wave can be observed. Following Fig. 3 shows the radial pulse wave.

Few *Nadi* parameters have scientific importance and can be compared with the modern parameters of any waveform. Table 2 shows

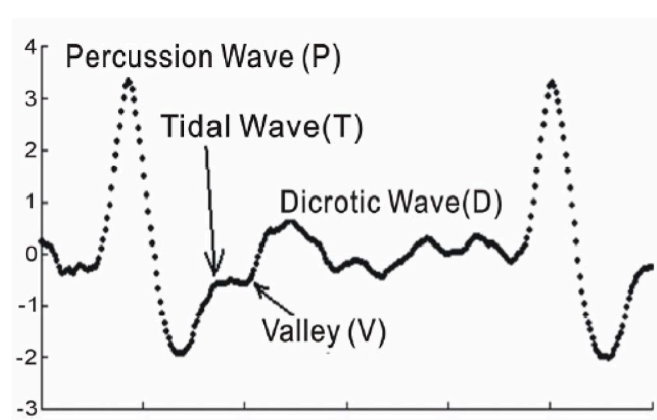

Fig. 3. Radial Pulse Pressure waveform [3].

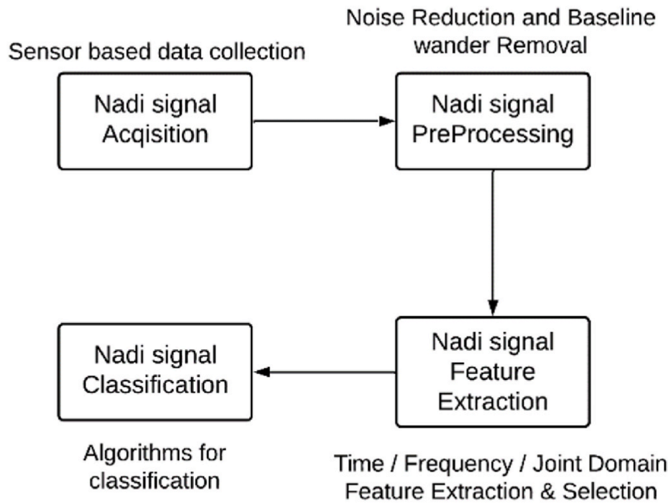

Fig. 4. Nadi *Pariksha* phases.

Table 2
Resemblance with scientific parameters.

Traditional Parameter	Scientifically associated parameter
Gati (movement)	Time required to reach from one peak to another peak
Vega (rate)	Pulse wave velocity (PWV)
Tala (rhythm)	Pulse rate variability (PRV)
Bala (force)	Augmentation Index (AI)
Akurti (tension and volume)	Stiffness Index (SI)
Tapamana	Temperature
Kathinya (consistency of vessel wall)	Blood Pressure

these parameters with their strongly associated scientific parameter.

2.3. Gati (movement of Nadi)

The *Dosha* predominance is a major wellness parameter in the Ayurveda *prakriti* and is very well examined by the practitioners by checking *Nadi Gati*. These movements are named according to the movements of animals and birds. These comparisons are useful in diagnosing diseases rather these are used as standards to diagnose any disease at first examination of *Nadi*. To elaborate one can, compare the curved movement of the snake, and leech to indicate the *Vata Nadi*. Compare the hopping, and jumping nature of frogs, and crows with *Pitta Nadi*. Compare the slow movement of the swan, elephant with *Kapha Nadi*.

A few times all three *Doshas* are aggravated. Traditionally Ayurveda practitioners do trust *Nadi Gati* for diagnosis. When arterial pulse waveform is plotted and compared with traditional parameters, pulse movement is the parameter that we need to take into consideration. Joshi et al. [4] compared the *Gati* parameter of normal and diseased persons and got amazing results. Still, more validation is required to state the physiological significance of *Gati*, and how it progresses during *Tridosha's* presence in the human body. It is a need for time to focus on its validation in measuring and predicting health conditions. Table 3 shows various *Gatis* and their nature. Table 4 shows various *gatis* written in *Ayurvedic* literature concerning health conditions.

Table 3
Various *Gatis* and their nature [1].

	Vata	Pitta	Kapha
Gati	Snake, Leech	Manduka, Crow	Swan, Elephant
Nature	Curved, Zigzag	Hop, Jumping	Slow

Table 4
Various *Gati* and their related indicators [1].

Gati		Health Conditions
Sarpa	Snakes	Normal *Vata*
Manduka	Frog	Normal *Pitta*
Hansa	Swan	Normal *Kapha*
Jaluka	Leech	Arthritis, Goat
Krumi	Worm	Parasites, Worms
Pippilka	Ant	Terminal Illness
Mayura	Peacock	High Cholesterol, High BP
Tittrika	Partridge	Gastric Ulcer
Lavaka	Quail	Prostates
Kaka	Crow	Aortic regurgitation
Kapota	Pigeon	Bronchial Asthma
Kukkuta	Cock	Diabetes, albuminuria
Ushtra	Camel	Aortic stenosis,
Gaja	Elephant	Lymphatic obstruction
Girija	Mountain	Heart Block
Visham	Irregular	Pulsus alter nans
Damaru	Vibrating	Fatal illness, renal failure
Padma	Lotus	Perfect health

Gati stands out to be a more important parameter when the human body shows more than one *Dosha* dominance. Table 5 shows how *gati* varies according to aggravated *dosha*. Table 6 shows various *gatis* observed during a specific *dosha* aggravation.

2.4. Vega (rate –speed of the pulse.)

Various important health conditions could be measured using physiological, psychological, and pathological parameters. *Nadi* has many parameters. Table 7 shows how *Vega* varies according to the health condition.

Vega (pulse Rate) is a widely used measure for primary clinical assessment. There are numbers of sophisticated instruments to note down the readings. If compared with arterial waveform, the Pulse Wave Velocity (PWV) becomes another significantly important pulse parameter. Focused research is indeed required in the *Nadi Pariksha* field for PWV. Kozo Hirata et al. [5] conducted a study to check the effect of various health conditions on the PWV. PWV is nothing but the space between two evaluating locations of the pulse. It ranges from 5 to 15 m/s. Studies also state that variation in PWV predicts many mortality-causing cardiovascular events. PWV increases with age, atherosclerosis, and blood pressure. Hence Cardiovascular physicians consider PWV for better diagnosis. PWV can closely be associated with *Vega*; therefore, the variations in *doshas* can be well measured using PWV [5,6], which are shown in Table 8.

PWV stands out to be an important parameter to study *Dosha's* presence and clarification [5]. PWV can bemeasured using equation (1).

$$\text{PWV} = \frac{\text{Arterial Distance (Two Pressure Points)}}{\text{Time (Travel from one point to other point)}} \frac{\Delta z(p1 - p2)}{\Delta t} \tag{1}$$

PWV parameter has recently gained scientific significance in the study. It is a significant indicator of cardiovascular disease. Though the immediate context is not available, if *Ayurveda* practitioners consider PWV for *Tridoshas* diagnosis, it will be fruitful. The validation of PWV is to be done in coming Technological advancements in *Nadi Pariksha.* PWV can be one of the valuable parameters in predicting cardiovascular mortality which is a major concern to the medical fraternity.

Table 5
Various *Gati* and *dosha* [1].

Nadi Gati observed	Aggravated *doshas*
Sarpa + Manduka	*Vata & pitta*
Sarpa + Hansa	*Vata & kapha*
Manduka + Hansa	*Pitta & kapha*

Table 6
Various *Gati* and *dosha* [1].

Vata	Pitta	Kapha
Sarpa (Cobra)	Manduka (Frog)	Hansa (Swan)
Jaluka (Leech)	Tittrika (Partrge)	Hasti (Elephant)
Krumi (Worm)	Kaka (Crow)	Padma (Lotus)

Table 7
Variation in *Vega* [1].

Feelings/Health Condition	Variation in *Vega*
Anger, Exercise	Fast
Sorrow, Fear	Slow
Fast Metabolism	Fast
Slow Metabolism	Slow
Tall	Slow
Short	Fast

Table 8
Variation in *vega* due to age [1].

Dosha	Vata	Pitta	Kapha
Vega	Fast	Medium	Slow
Age	Old age	Middle Age	Childhood

2.5. *Tala (rhythm) or sthiratva (stability of pulse)*

Tala is the time gap between 2 sequential uplifts. In any healthy person, *Nadi* is rhythmic with regular intervals. According to *Basavarjeeyam* and *Yog Ratnakara* the *Nadi* which is irregular and feels at a different location is termed as *asadhya Nadi* and may be denoting near-death in many cases hence it is called as *mrityu Nadi* also.

2.5.1. *Pulse rate variability*

Pulse palpation is used to compute the rhythm. Nowadays instruments can perform pulse acquisition in the form of time-domain, frequency domain or joint time-frequency domain features. The PRV can be associated with HRV (Heart rate Variability). According to Ayurveda literature equivalent term for PRV is not found in texts but it can be strongly associated with sthivatva. PRV changes according to the health conditions, disease present and psychological condition.

Table 9 shows variation in *tala* according to the physiological or psychological condition.

Joshi et al. [4] have conducted the study for PRV using *Nadi* Tarangini (A pulse diagnosing device) and found that there are variations in *Nadi* rate with age. Pulse duration increases as the age increases. Same observations are noted by Refs. [7,8]. There are significant variations according to disorders and age in the pulse intervals of the artery. PRV could be seen in the time and frequency domain. Recent advancements must be focused on PRV for pulse stability and rhythm to study *Tridoshas* in detail.

2.6. *Kathinya (hardness of artery)*

According to the text, the resistance due to the rough and hard nature of the artery means *vata dosha*. If the blood flow is fast, *Nadi Kathinya* is increased. *Nadi kathinya* is observed to be moving slowly in curved nature. The vessel wall consistency, which could be examined between the respective finger and the radial artery (wrist), is identified as *Kathinya*. On increasing pressure on the *Nadi,* practitioner can find the thickness, elasticity, and rigidness of *Nadi* to decide the *kathinya*.

Table 9
Variation in *Tala* [1].

Physiological or psychological	*Tala*
Healthy	Strong regular
Just Had food	Regular
Hungry	Irregular
Vata	Irregular
Pitta	Regular
Kapha	Regular

2.6.1. *Arterial stiffness*

Age and atherosclerosis are the major factors why *Nadi* thickness is increased [9]. Patients with hypertension may cause mortality due to cardiovascular and coronary events. Arterial stiffness is the primary indicator of such events [10]. Thus, the stiffness index (SI) is the indicator of arterial stiffness. Which could be measured as a volume pulse using a photoplethysmography (PPG) sensor [11]. *Nadi*-Tarangini like device has shown that when the pulse is acquired at the *vata* location, it shows notably different values for Diabetic and non-Diabetic patients [4]. For non-diabetic patients, SI is inversely proportional to fasting plasma glucose [12]. SI measured from the radial artery has a significant role in the Ayurveda. SI, if measured from peripheral arteries, does not give us the correct result. This happens because multiple reflections from various reflection sites are continuously received, and central arteries are away from these sites as compared to peripheral sites [10,13]. Hence radial artery demonstrates a key role in measuring SI which in turn is used in *Tridoshas* Analysis. Hence it is required to study more about *Nadi Kathinya* in the context of *Tridosha* analysis. SI can be measured using equation (2) [].

$$SI = \frac{\text{height of the person}}{(\text{time period at diastolic peak} - \text{time period at systolic peak})} \quad (2)$$

2.7. *Bala (force)*

Bala is the *Nadi* pressure, which the practitioner feels while examining *Nadi*. If the pressure on *Nadi* is increased, the same amount of pressure is exerted back onto the finger. Augmentation Index is the pulse pressure (PP) ratio to augmentation pressure (AP) and is calculated using equation (3), which needs equations (4) and (5) at backend for calculation.

$$\text{Augmentation Index} = \text{AP}/\text{PP} \quad (3)$$

$$\text{Pulse pressure(PP)} = \textit{Systolic pressure} - \text{ Diastolic pressure} \quad (4)$$

$$\text{Augmentation pressure(AP)} = \text{Systolic pressure} - \text{ Inflection point pressure} \quad (5)$$

The inflection point is the point where the concavity of the curve is reversed [14]. For every individual, according to Prakriti and blood volume *Bala* may get varies.

2.8. *Akriti (tension and volume)*

Volume and tension at the artery are referred as Akriti. Uplift sensed to finger is volume. The volume of the pulse relates to the amount of blood that is pumped out during the systolic phase. Low volume indicates low systolic blood pressure and high volume indicates high blood pressure. If the ring finger is pressed up to the level that the radial blood vessel stops pulsating, that tension is felt and used for diagnosis. *Nadi* Tarangini [4], and *Nadi* Yantra [3] are the devices designed & developed to acquire *Nadi* signals at *Vata*, *Pitta*, and *Kapha* Locations. Many more researchers have also focused on the stiffness index as an important parameter. Using Tension & Volume Ayurveda practitioner can determine blood pressure without Sphygmomanometer. Table 10 shows *Bala* and *Akruti* variations for trishodas.

Table 10
Variation in *Akruti* due to age [1].

Dosha	Vata	Pitta	Kapha
Akruti	Low	High	Moderate
Bala	Low	High	moderate

2.9. *Tapamana (temperature)*

Texts have stated that there is a relationship between *Nadi Gati* and *Nadi* Temperature. Agni or the metabolic fire is related to *Nadi* Temperature. Table 11 shows the varied tapamana, as shown in Table 11, for *Vata* dominance *Nadi*'s temperature remains cold; for *pitta*, it becomes hot, and for *kapha* nature, it stays warm to cold.

3. Components of the automated *Nadi Pariksha* system

Nadi Pariksha, when done using any technical equipment, the signals are captured using sensors and can be plotted in wave format. These waves can be labelled commonly, as shown in the Fig. 3. The heart systole status is shown mainly by percussion wave, whereas the tide wave, valley, and dicrotic wave are changed due to arterial compliance, peripheral resistance, vascular elasticity, cardiac activity, and other physical properties [15]. The traditional *Nadi Pariksha* (TNP) system involves three stages, Pulse taking, Pulse feeling, and Diagnosis. Automated *Nadi Pariksha* simulates TNP in four phases. Fig. 4 illustrates the major phases of the automated systems.

Multiple reviews like [16–18] help us understand the process, its significance, and future directions from various development in traditional radial pulse diagnosis.

This paper gives full coverage for traditional *nadi pariksha* simulated using automated *nadi pariksha*, the novel research done in recent years in this field in countries like India, China, Japan, and Korea.

3.1. *Nadi signal acquisition*

This module acquires the *Nadi* signals with quality and resolution. Many devices invented uses their own acquisition system. Generally, this system is based on some sensors. Data collected from sensors is given to next module. Generally, this module has two subcomponents. 1) Sensors for data collection 2) Attachment covering VPK locations on the wrist. Researchers have used Data Acquisition card NI USB – 6210, Bio PAC 150 TM [4].

3.1.1. *Nadi Pariksha sensors*

Ayurveda believes in *Sparshna, Darshna, and Prashna* techniques to diagnose diseases. In any ANP, the Sparshna phase is deployed using a sensor, three sensors for *VPK* are installed, and signals are captured, which are analyzed using any statistical or machine learning based classification method. Sensors have issues related to the accuracy, sensitivity, and interference with other sensors and are well addressed in Ref. [19]. These issues need to be addressed. Some researchers have used single probe systems, whereas most have developed a three-probe (*VPK*) system or even multiple probes for various pulse locations.

Acquiring the *Nadi* signal is the major task. *Nadi* waveform is taken via a sensor system. Each of the sensors used, shows certain pros and cons, while you discuss the accuracy, sensitivity, interference with other sensors, etc. A lot of work has also been done in Traditional Chinese Medicine (TCM). This sensor system till now have used piezoelectric sensors, magnetic sensors, infrared sensors, optical and photoelectrical

Table 11
Variation in Tapamana due to *dosha* [1].

Dosha	Vata	Pitta	Kapha
Tapamana	Cold	Hot	Warm to Cool

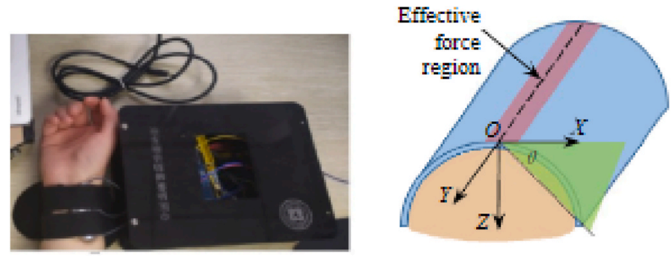

Fig. 5. Unit with piezoelectric sensor A301 [25], bending area [23].

sensors, doppler ultrasonic devices, pressure sensors, even MEMS (Micro-Electrical-Mechanical-System) was used, array of sensors also been used in the TCM systems. The raw signal obtained from *Nadi* via these sensors typically has lesser signal to noise ratio and shorter amplitude which is required to be amplified and filtered with the help of adequate setup. After acquisitioning these signals need to be converted to digital format via A/D convertors. Researchers need to keep this in mind and choose an adequate sampling rate and resolution [20]. Joshi et al. [4] for an instance have used a 16-bit digitizer with 500 Hz sampling rate.

Three sensors near each other produce three perfect waveforms showing *Vata, Pitta, and Kapha* signals. After this, these signals must be converted to digital format via A/D convertors.

Using these pulse waveforms, researchers have predicted various diseases. Various researchers have worked in pulse diagnosis using multiple sensors. Table 12 exhibits the type of sensors and reference paper of their appearance.

This section covers the detailed study of the above-listed sensors.

3.1.2. *Pressure sensors – piezoelectric & piezoresistive*

Nadi (Radial Artery) Signals are pressure signals. Researchers have used pressure sensors to sense this pressure data from *nadi* location. Pressure sensor generally converts mechanical pressure to electrical signals. Place 3 pressure sensors at VPK position and get the electrical signals, this will help in plotting the signals and get digitized data from it. Pressure sensors to be used for this purpose are piezoelectric, piezoresistive, and strain gauge.

The piezoelectric effect produced by some material is their ability to produce electric signal in response to mechanical pressure. 'Piezein' in Greek means to sequence or to press. Hence piezoelectric effect is used by piezoelectric sensors to measure changes in temperature, pressure, strain, etc by converting it to electric signals. *Nadi* pressure is dynamic in nature and piezoelectric sensors works good with dynamic pressure and not with the static pressure. Piezoelectric transducer (Flex Force A301) was developed in round shape with diameter 0.375 -inch, 0.55-inch in width, and 1-inch in length as available sensing area, the force ranged 1–25 pounds and it is used to study the signals [25].

Bhinav et al. [3] also used piezoelectric sensors to monitor pre- and post-lunch, dynamics of the radial artery signal changes on the application of a stimulus. They used BioPac 151 M as a data acquisition system. Pressure wave decomposition using wavelets done for Analysis. Series of amplifiers are used to amplify and filter the obtained signal.

Table 12
Summary of sensors used.

Sensor	Reported in
Pressure – Piezoelectric, Piezoresistive, Strain Gauge	[3,4,21–26]
Optical/Photoelectric	[26,27],
Image	[28–30]
Pulse	[31–33]
Pulse acoustic	[34]
Doppler Ultrasonic	[35,36]
Array of sensors	[22,24,37,38]
PVDF	[39]

They have used NI USB -6210 for data acquisition. Shape, rhythm, amplitude-frequency, and pulse were captured and analyzed using ANN. Kritika et al. [40] have used Piezoresistive sensor MXM 2053D, instrumentation amplifier INAJ28 and DAC card my RIO for data acquisition. This sensor comes in dimension 9.1 mm × 7 mm hence suitable to be placed or worst at 3 locations to trace vata, pitta, Kapha. It provides measurement within the range of o to 375 mm of Hg. They concluded that results from sensor signals are useful to distinguish between healthy and unhealthy subjects. Fig. 5 shows the same sensor.

Piezo resistive sensors are other type of pressure sensors and utilized effectively for pulse examination. Piezo resistive material helps changing the resistance to the flow of current with operated pressure (strain) in these sensors. They use several thin layers of semiconductor silicon and Wheatstone bridge used to detect small changes in resistance. When current is passed though the sensor, when the resistance changes, less current passes though the pressure sensor.

Blood flow, Heart rate, blood volume, blood viscosity is analyzed to go on predicting some diseases. PWV can be measured using this sensor in much better manner and is used to note the pulse wave, pulse wave velocity and BP (blood pressure) [21]. The fabricated sensor chip is shown in the Fig. 6.

3.1.3. Optical sensors

Optical sensors can sense light, ultraviolet rays, visible infrared light. An episode where electrically charged particles are liberated from or within an object on absorption of electromagnetic radiation is named as photoelectric effect. Ejection of electrons happens from a metal plate when light falls on it. This universal phenomenon is used in the working of optical sensors. Due to this photoelectric effect, the optical sensor identifies either frequency, wavelength, or polarization of light and transforms it into an electric signal. Deepa et al. [27] have mentioned that PPG signals shows the blood volume shifts. The light intensity passes across or threw back from skin varies as blood flow rate varies, this radiation is generated due to pulsation, and hence if placed on VPK points, produces output. PPG sensor which includes an infrared LED (HSDL -4420-875 nm), and photodiode (HSDL5400) is used to capture signals, which are analyzed using LABVIEW software. Mean values of these signals were calculated for various age groups to check the *Doshas* dominance. Here Sparshna phase is deployed using an optical sensor, 3 sensors for VPK are installed and signals are captured, which are analyzed using ML Algorithms to distinguish anaemia and hyperacidity

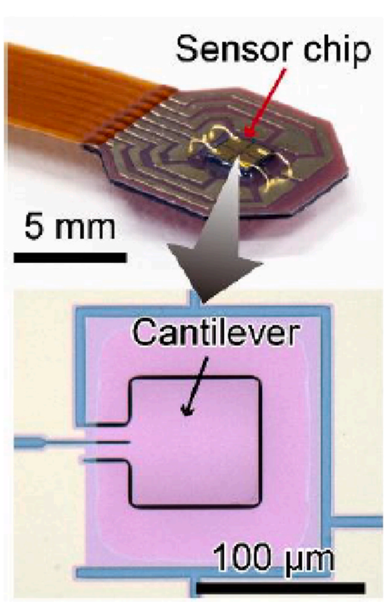

Fig. 6. Fabricated sensor chip [21].

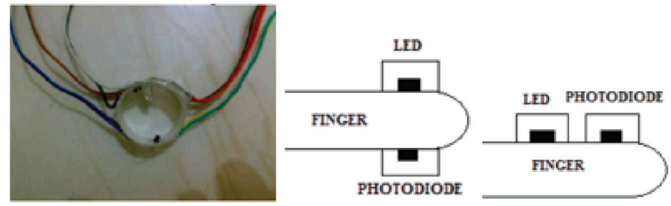

Fig. 7. PPG Sensor in transmission and reflection mode [27].

patients. Fig. 7 shows the PPG sensor used in pulse acquisition.

3.1.4. Image sensor

Light and colour spectrum is converted to electrical signals, in the form of 0s and 1s, which in turn used by the camera in an image sensor. CMOS (complementary metal oxide semiconductor) and CCD (charge-couple device) are the two very familiar technologies utilized in image sensors.

Xue et al. [29] have tried developing a 5D pulse acquisition system using digital image correlation. This system records skin fluctuations under various pressure conditions. After acquisition, the signal is analyzed for amplitude, pressure, and pulse wave velocity.

Image sensors nowadays gaining more attention in biomedical devices due to their features like lightness, softness, and bendability. As light can detect much more important information from a human body, these flexible image sensors can be used for attaching to curved surfaces over skin. It gives continuous data with high accuracy [41]. Fig. 8 shows the setup of pulse acquisition system and the image captured in the process.

3.1.5. Pulse sensors

This sensor sends IR Light into the artery, and the sensor captures the amount of light reflected. This difference between incident light and reflected light generates a signal. The LED throws light on the capillary tissues, and the amount of light reflected is used to calculate the pulse signal. This is 10 × 10 mm in size, and three side-by-side sensors can capture *Vata, Pitta, and Kapha*. Noise can be removed using LABVIEW-designed filters. Chaudhari et al. [32] used an IR based PPG sensor. Pavana et al. [31] have used the pulse sensor to acquire signals from *Nadi Pariksha* yantra and compared the performance of Bessel and Butterworth filter. Authors concluded with the result that 8th order Bessel filters can be used in better manner to remove overshooting and ringing effects, as well as to maintain the periodicity of *Tridosha* signals [31]. Dubey et al. has used pulse sensor along with launchpad to analyze the pulse data digitally. Authors implemented cloud storage to demonstrate remote health monitoring [33].

Fig. 9 shows a standard pulse sensor.

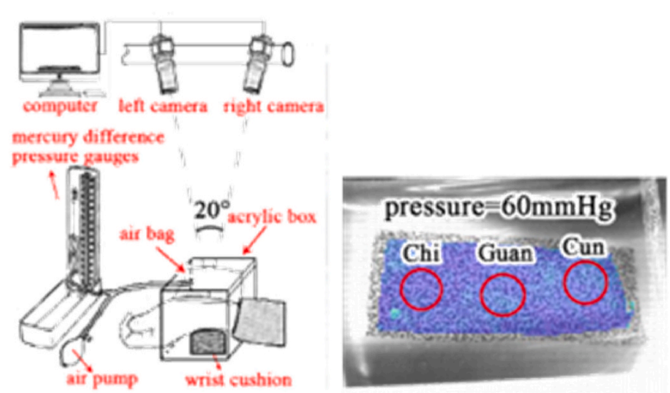

Fig. 8. Image capturing system and positions of pulse in captured image [29].

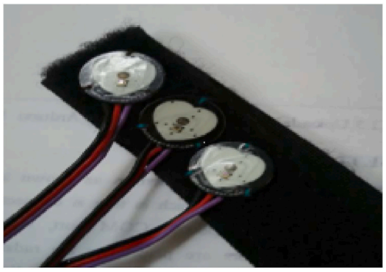

Fig. 9. Pulse sensor [31].

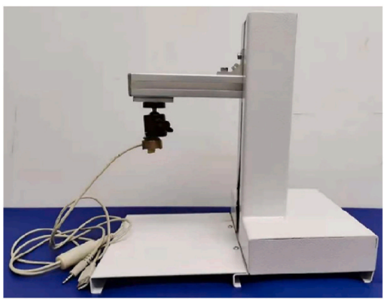

Fig. 10. Setup with acoustic pulse sensors [34].

3.1.6. *Pulse acoustic sensor*

Cui et al. [34] have used pulse acoustic sensors to detect stable coronary heart disease. Pulse can be divided into five layers at any one point in TCM. The acoustic sensor comes with excellent performance. The acoustic sensor detects sound and converts it to a signal. Researchers have tested 90 subjects for healthy and stable CHD and got good results while analysing. Among the five layers, it is found that 3rd & 4th level gives more identifications for stable CHD. Fig. 10 displays a pulse diagnosis setup with the acoustic sensor.

3.1.7. *USB based Doppler ultrasonic blood analyser*

Basically, Doppler ultrasonic blood analysis work on the principle of the Doppler Effect. Signals (sound, light, or waves) are either increased or decreased as the source and observer come closer or go away from each other. This effect is called as Doppler Effect. The sensor can sense the moving particles in blood by measuring sound waves and those signals can be used to perform pulse diagnosis. Chen et al. [35] have used a single probe (*Pitta* position in Ayurveda) with an ultrasonic blood analyser device. By varying the probe. This Doppler device has attained 94.5% accuracy in diagnosing if used along with the Gaussian model after modification [35]. The accuracy of up to 80.77% and 86.21% is achieved in discriminating Gastric, Cholecystitis patients from healthy persons [42]. The signal from the doppler device can be analyzed using HHT (Hilbert. Huang transform method) to obtain 100% accuracy in classifying different patients [36]. Fig. 11 shows a typical spectrogram.

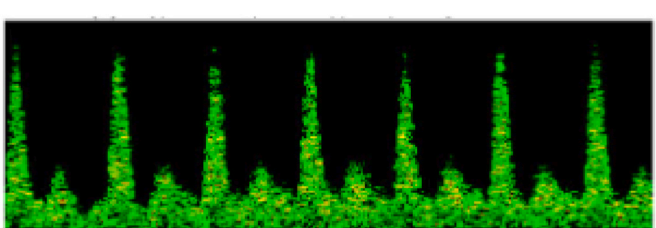

Fig. 11. A typical wrist pulse doppler spectrogram [35].

Fig. 12. Levels of *Nadi* described in Texts [1].

3.1.8. *Array of sensors*

In Ayurveda as well as in TCM, it is effective to gather pulse data from three positions with changing stationary pressure. This type of data acquisition is not possible with a normal 3 sensors device. Array of sensors means a group of sensors usually fixed in a specific geometrical pattern as per the requirements. These sensors can be selected from the range of sensors. In ayurveda various diseases can be identified using 5-level or 7 level *Nadi pariksha method.* Even on the single finger, different positions, various interpretations can be done. Fig. 12 shows those various levels which are felt at various points of finger.

This concept from text was developed using the array of sensors. BSPDI (Bi-Sensing Pulse Diagnosis Instrument) is the device built on this concept. JPD (Jin's Pulse Diagnosis) is another device, in this device fibre optical sensor is used to sense radial artery [22].

Zhang et al. [22] have used a fibre optical sensor to prepare a device for radial artery pulse diagnosis in TCM. An iterative sliding window algorithm was used for analysis. Each location has three different signals generated; these signals may give us a minute level of information. An iterative sliding window algorithm provides work flexibility and shows a substantial variation between pulse-taking depth and position. The pressure exerted by the physician on the pulse is a significant factor for analysis [37]. The device BSPDI is shown in Fig. 13.

The same device can be used as the Three Positions Nine Indicators (TPNI) concept [37]. The study was carried out to check the significance of depth or pressure on pulse and pulse-taking positions.

3.1.9. *PVDF material based pulse sensor*

PVDF stands for Polyvinylidene Fluoride which is also referred to as PVF2. It is the most used commercial and industrial coating available. It provides excellent resistance from metal weathering over time. PVDF is an utter thermoplastic fluoropolymer and extremely non-reactive. Using the sensor based on this material, without exerting much pressure the pulse data can be collected. This data collection is effective. The system using PVDF sensor provides accuracy, while the system continuously observes breathing and pulsation in real-time. As the sensor is supple in nature, it is easy to use it in wearable monitoring devices [39]. This sensor may provide good results for identifying *Vata*, *Pitta* & *Kapha* constituents also. Fig. 14 shows PVDF material used in making of sensor.

3.1.10. *Attachment covering VPK locations on wrist*

Acquiring the pulse data must be a contactless method. This setup requires 3 sensors probe to be placed on correct VPK positions on wrist.

Fig. 13. Photograph of BSPDI [37].

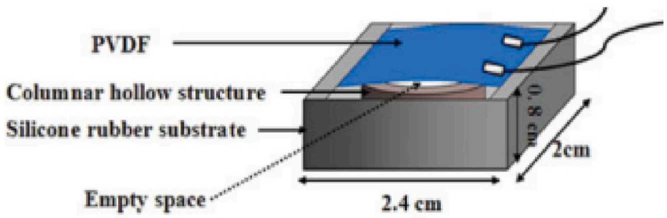

Fig. 14. PVDF pulse sensor [39].

Placing the probes on right position and pushing with correct contact pressure, get this setup connected with analysis is required [3,43,44]. The trained data collector or the physician must first determine the correct positions on the wrist and then once the optimal positions are determined, these sensors must be attached to the wrist. Any wrap around band or glove can be prepared and these sensors need to be mounted on it.

Fig. 15 shows various setups researchers have adopted to fetch the data. Some have used a pressure cuff to hold down the pressure on the wrist. On the contrary, it is also observed that varying contact pressure may lead to other problems, such as blood flowing in the backward direction, blue skin etc. Contact and non-contact pressure sensing also make a difference. The sensor's sensitivity also makes a difference in sensing the pulse waveform. Pressure and proximity can be collected through one single system. Mechanical screws are used to create repeatable hold-down pressure, with varied level. Other reported the use of stepping motors, micro-motors, and a corresponding control unit to apply external hold-down pressure [45]. Fig. 15 shows different kinds of setups using various kind of sensors.

3.2. *Nadi signal pre-processing*

Acquired Nadi signals required to be processed, as the signals may contain some noise. This noise could be created due to respiration, movement, stress, or other external factors. When the sensor encounters skin and wrist band, it generates noise. Elimination of such interference factors is much necessary, prior to analysis of signals. Many researchers have developed filtering techniques to reduce signal to noise ratio. Butterworth low pass filter designed in LABVIEW Software can be used efficiently. To calculate low pass cut-off filter frequency, equation (3) is used [46].

Fig. 15. Pulse measuring setups.

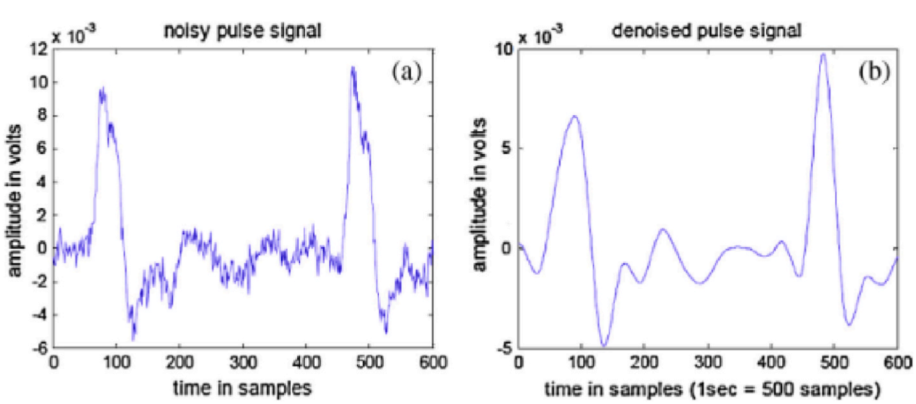

Fig. 16. Signal pre-processing [51].

$$fc = \frac{1}{2\,\pi Rf Cf} \tag{3}$$

Rf and Cf are the resistors and capacitors, which are frequency-determining components.

TCM also have worked using wavelet transform technique which is deployed by Refs. [46–50]. Baseline wander is also created due to respiration, movement, or poor sensor contact. Baseline wandering interference misleads from accurate identification. This baseline wanders removal is one of the essential steps in signal pre-processing. Baseline wander is a low-frequency noise that needs to be removed. The wavelet transform method seems to be the most effective way to remove 'Baseline wander [3]. After noise reduction, certain signal processing approaches are used such as segmentation and outlier removal. Researchers have used Data Acquisition card NI USB – 6210, BioPAC 150 TM [4].

Fig. 16 shows the noisy and denoised signal.

3.3. Feature extraction using time and frequency domain features from Nadi signal

Next to pre-processing, feature extraction is also an important step. The purpose of feature extraction is to generate a non-redundant, revealing vector of the original signal. For this purpose, researchers have tried many different methods.

Researchers have analyzed the pulse signal more in Time domain, as time domain features provides more information about the clinical relevance, these signals are straight forward and offers temporal data, events such as systolic and diastolic peaks, etc [16]]. However, in some cases the frequency domain features are also useful and gives clear insight for the disease diagnosis. For example, HRV (Heart rate variability) requires the frequency features to be used. The power spectral density of the pulse signal may be analyzed to identify frequency components associated with autonomic activity [52].

This section of the paper gives brief idea about these methods. Section 3.3.1 explains use of time domain feature extraction and section 3.3.2 explains frequency domain feature extraction.

Following are the few features, used by many researchers for analysis. To name a few, rising and falling peaks, pulse wave velocity, Augmentation Index (Stiffness), and Reflectivity Index (Blood Volume) [14]. Pulse repetition rate, pulse frequency, and pulse amplitude, Percussion peak, dicrotic peak, pulse ascent time, descent time, diastole time [51]. Wiry, slippery, hesitant, chord, flat [53] etc. these features can be obtained from extraction methods. Approximate entropy was used by Chaudhari et al. [32] for analysis. Rising and falling peaks, pulse wave velocity, Augmentation Index (Stiffness) and Reflectivity Index (Blood Volume) are used by Kadarmandalgi et al. [14].

Sample entropy, multiscale entropy, Frequency and its harmonic frequencies, frequency shift, phase shifts, power, energy are also the features which are used in analysis [17,54]. For this purpose, researchers have tried many different methods. Mainly time domain feature extraction [3,4,34] and frequency domain feature extraction methods are used [14]. Few researchers have also implemented joint time-frequency domain features extraction and analysis, it may provide a next level possibility to analyze the Nadi signals [20,47,55].

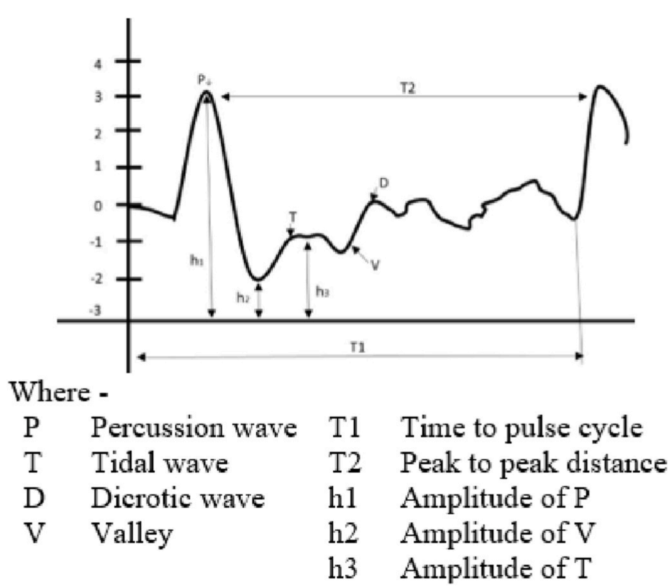

Fig. 17. Time domain features.

3.3.1. Time domain analysis (TDA)

Time domain features have their own advantages, they are quite straight forward to summarize and understand, as well as they are having much physiological significance [14,47]. Still there is one issue with these parameters that sometimes the tidal and/dicrotic waves are very weak and cannot be read. In turn makes it difficult to determine the exact values of features. Tidal waves, Percussion waves, valleys, dicrotic waves are the parameters used to extract features [3,4]. Time domain assessment examines pulse appearance, its shape, and its contours. It is observed that the pressure pulse waveform includes percussion waves, tidal waves, and dicrotic waves. In a standard pulse amplitude of peak, dicrotic notch, and resultant time-gaps are the parameters used to analyze the health status of humans. The low amplitude of the tidal waves and dicrotic waves indicate an imbalance in human health. Higher alterations in the pulse diagnosis were observed in unhealthy subjects compared to healthy subjects [56]. Fig. 17 shows time-domain features.

3.3.2. Frequency domain analysis (FDA)

After the time domain, FDA is the widely used approach. It is built on feature extraction in the frequency domain. Certain physiological and pathological conditions of human health can be explored using FDA. Arteries supply fresh blood to human organs like kidney, lung, spleen, and liver for their proper functioning. Every organ that propels the blood out, which produces oscillations in the ascended waves. This will transform the frequency spectrum of these waves. These waves will carry data about that organ, and practitioners check it at the radial pulse [25]. It is observed that each organ has a different resonant frequency. The frequency features store important pathological and physiological data about that organ. Extracting the data will help us know the organ better, this extraction is mostly done using FFT (Fast Fourier Transform). Zhang et al. [36] have suggested using Hilbert Huang transform (HHT) for spectrum feature extraction. Huang et al. [53] also have worked with wiry, slippery, and hesitant pulse to extract features. Table 13 shows the list of frequency domain features.

3.3.3. Joint time-frequency analysis

Joint domain analysis includes features from Time domain as well as frequency domain. Joint time frequency analysis can explore new possibilities of pulse diagnosis [47]. In TCM joint time-frequency domain analysis was also used by a few researchers. Short time Fourier transform, or wavelet transform can obtain the data for analysis [55].

Table 13
List of frequency domain features.

Frequency Domain Features	Reported In
Frequency and its harmonic frequencies, frequency shift, phase shifts, power, energy	[17]
Sample Entropy, multiscale entropy	[54]

3.3.4. Feature selection

Redundant and irrelevant data in the dataset lead to performance degradation. Hence suitable features must be supplied to the classifier. These features can either be chosen manually by experience, one can use the pilot method, or an automated features selection method can help in this procedure. So, dimensionality reduction techniques and feature selection techniques should also be considered before classification. Researchers have suggested many different methods to be used for it. Classifier-dependent feature selection algorithms like SVM, naïve Bayes, decision trees, and neural networks can also be used. Statistical methods or hybrid feature selection and reduction techniques which includes the feature selection methods like Mann-Whitney, *t*-test, Bhattacharya distance, etc can be used for feature selection. Feature selection is used for biomedical signal processing are well discussed in Ref. [57].

3.4. Nadi pariksha result classification and objectives

The disease prediction after pulse diagnosis varies from practitioner to practitioner. The automated tool may classify the disease depending on the information collected. Once appropriate features are obtained, they can be supplied to the classification technique. The classification technique is an algorithm that will distinguish between the subjects based on healthy and unhealthy or any kind of disease. Depending on the values received for every parameter in the data set, the classifier will classify each signal into one of the classes. For this purpose, many more classification approaches were suggested. Most researchers have used either linear statistical methods to come to any conclusion or applied supervised machine learning algorithms or neural network algorithms.

3.4.1. Classification objectives

1. Distinguishing Healthy Subjects versus diseased subjects
2. To identify the Dosha Dominance, i.e., Vata, Pitta, and Kapha percentage presented in subjects Prakriti (Prakriti Analysis)
3. To identify pathological conditions like blood sugar and blood group with this non-invasive approach.
4. To identify some mental/mind-related Syndromes.

3.4.2. Diseases diagnosed

This paper tried to discuss various researchers' efforts in predicting or diagnosing diseases like dosha dominance, hypertension, diabetes, sleep, mental stress, heart disease, gastritis, Cancer, Kidney failure, lung cancer, pregnancy, Pancreatitis, Duodenal Bulb ulcer, Nephritis, Cholecystitis, Gastritis etc. Diabetes is one of the most diagnosed diseases using pulse diagnosis.

3.4.2.1. Machine learning and related approaches. Joshi et al. [4] has applied a machine learning algorithm to classify patients with heart rate variations or mental stress. Various algorithms such as back propagation, neural networks with hidden layers, SVM, decision tree, KNN, random forest etc are explored by the researchers to get the accurate output.

3.4.2.2. Statistical methods and tools. Researchers have used statistical tools such as R, SPSS, Excel, and MATLAB to compute standard statistical operations. Sebastiao et al. [58] have discussed various statistical tools and methods used in healthcare analysis. Chu et al. [37] have explored using Anova, Analysis of variance with the SPSS tool. Duprez et al. [59] have also used statistical methods like RMSD, SD, Variance, etc. Deepa et al. [27] commented on *Dosha*'s dominance concerning age using statistical methods applied to the features extracted from *Nadi* patterns. Table 14 summarizes the multiple techniques for a disease diagnosis. Table 15 shows the overall summary of literature review.

Dubey et al. verified a statement from Ayurveda that VPK changes according to daytime. Authors tried using statistical methods to find mean of peak difference for Vata, Pitta and Kapha for different age groups. The experiment resulted in saying, vata is dominant in evening, whereas Pitta in afternoon and Kapha in morning session [33].

Table 14
Summary of diagnosed diseases and algorithms used.

Disease diagnosed	Machine learning ML/Deep Learning DL/Neural Network NN/Statistical methods Stat
Dosha Dominance	NN [14] [27], Stat [60], Stat [33]
Unhealthy person	SVM, KNN [61]
Heart, HRV	ML [4], Stat [13], Stat [34], Random Forest [62], Peak Detection [63]
Sleep monitoring	threshold [52]
Diabetes	KNN, RBF-SVM [24], CKL [26], SVM [64], kernel SVM [38]
Lung cancer	Cubic SVM [35], Iterative slide window [22],
Mental stress	ML [4]
Pancreatitis, Duodenal Bulb ulcer	C means [35], SVM [65]
Nephritis, Cholecystitis, Gastritis	SVM [36], KNN SVM [61], 6 ML [66], SVC [67]
Hypertension	Stat [6,10]
Pregnancy Detection	RBF-SVM, KNN [24]

Deepa et al. [27] commented on *Dosha* dominance using satisfied methods applied on the features extracted from *Nadi* patterns. Kadarmandalgi et al. [14] have implemented statistical analysis methods such as mean, mode, median on the data-collected from *Nadi* pattern and analyzed the patients for specific disease or Prakriti *Pariksha*.

3.4.3. Challenges

There are various challenges in doing the nadi Pariksha accurately with sensors. This field is very new and progressive, Government is also supporting the innovation from various authors from the country [33]. While studying for the topic, authors encountered with below-mentioned hurdles. Finding subjects with multiple chronic diseases is a difficult task. That's why the number of subjects under consideration is less in much research conducted. Sample Population calculation is not based on any mathematical equation. Instead, the number of subjects involved by every researcher was significantly less. Probably, the inference drawn may vary if the population is increased.

Next, it is observed that models developed may have a high accuracy rate for specific diseases and only for some. Pulse waveforms of the same disease with different age groups may be different. Sensor choice is another major challenge as some sensors are more accurate towards specific parameters like blood viscosity, oscillating frequency, or blood volume, hence more precise towards diseases. It is also observed that pressure applied on three sensors may vary the result. As the pulse datasets for analysis are private, the performance comparison on a large scale cannot be performed. Hence the evolution of such equipment is only possible for a while. The main challenge is improving the precision and efficiency of the signal acquisition process; hence standardization of procedure, the main difficult task, is required. Due to a lack of domain knowledge expertise, standard equipment is still unavailable in the market.

Diabetes, Heart disease, and pancreatitis are the few diseases diagnosed frequently. Touching other diseases is beneficial to society. Researchers repeatedly use only a few machine learning methods. New untouched methods can be considered to check whether they can improve efficiency.

4. Conclusion

This paper reviews state-of-the-art development and technological advancements in Indian *Nadi Pariksha* techniques and some significant progress in TCM pulse diagnosis. The covered topics include sensors, signals from sensors, wrist attachment, signal pre-processing, feature extraction, feature selection, and classification. This can be stated that,

Table 15
Summary of literature review.

No	Sensor	Features	Feature extraction Feature Selection	Subjects	Disease diagnosed	Classifier	Results %	Reported in
1.	Pressure Photoelectric	Amplitude Tidal wave	improved Gaussian model	831	healthy vs. morbid Angiocardiopathy Nephrosis, Gastropathy	SVM KNN	82.13	[61]
2.	Pressure	Amplitude, Number of peaks Shape, Pulse duration 1D series to 2D matrix	Time domain Frequency domain Gaussian model	1554	Diabetes Nephritis Cardiopathy	KNN RBF-SVM	91.6	[24]
3.	Pressure, Photoelectric Ultrasonic, Combination	primary secondary peak Dicrotic notch TWED	Time domain Multipoint sample entropy	397 184	Diabetes Arteriosclerosis	Composite Kernel Learning (CKL)	91.65	[26]
4.	Pressure sensor 12 X 3 Sub sensor	pulse width period of the pulse depth of the valley	Entropy	398	Diabetes	SVM 10-fold cross-validation	92.6% sensitivity 87.6% specificity 90.2% accuracy	[64]
5.	Image sensors	Rhythm, shape Amplitude	Image processing FFT, moire patterns	–	Validate the pulse features	Matching patterns		[28]
6.	Pulse sensors	Peak Difference	Mean for VPK	120	VPK Dominance	Statistical Analysis	Verified with daytime	[33]
7.	Multichannel fusion sensor array	Amplitudes Periods, Pulse width intra-class distance wavelet coefficient	Time domain Frequency domain Frequency spectrum Proposed preprocessing	250	Diabetes	kernel SVM	91.6	[38]
8.	Piezoelectric sensor	Stability Index Concave structure index	Eigenvalues decomposition	60	changes in arterial blood flow normal, Pancreatitis, Appendicitis	Kernel SVM Linear classifiers	<90	[65]
9.	Doppler ultrasonic	amplitude and phase information	Higher order statistics (Bispectra) Pattern classification	142	Gastritis Cholecystitis, pancreatitis	soft margin SVM, 5-fold cross-validation	100	[66]
10.	Optical pulse sensor	10 Pulse features based on pulse amplitude	FFT, power spectrum graphs pattern recognition methods	50	Cold, fever back pain pregnancy	KNN, SVM LDA, QDA, DT	96.29% 90.9% 79.8%	[68]

although researchers in this area make considerable efforts, still the concept is in its budding state and need further research. It has been observed that the unification of devices for performing *Nadi Pariksha* is very much required.

Standardization in the sensors, probes, and data acquisition process is much required. The pulse image acquisition process also needs to have more research. *Ayurvedic* practitioners demand small, user-friendly equipment to analyze the *Nadi* patterns. More research must be done on the correlation between disease and symptoms. A user-friendly web application for pulse diagnosis is also a requirement of the era, which may be based on the *Prashna* and *Darshana* techniques.

According to the ancient texts, *Nadi* Pattern is driven only by pathological conditions but also by psychological factors and environmental conditions such as height, weight, time of the day, season, emotion, stress level, body frame, etc. The problem which is observed is that as the standard database is not available for *Nadi Pariksha*, the available system cannot be compared with each other, as their performance is dependent on various sensors, DACs, amplification techniques, signal processing techniques, classification aims, subject group, no. of the subject, age groups, etc. That's why authors recommend having a common database publicly available. This will lead to unambiguous system development.

While we discuss the future of the automated nadi pariksha, it can be used for patient monitoring systems in which the sensor-based device can be used to monitor patients round the clock [28,33]. These devices can be integrated with mobile to activate alert system. Going further this concept will help in developing home care system, as the system is non-invasive, can be used in home care systems [69]. *Nadi* analysis and *Tridosha* based wearable gadgets can be developed to monitor any subject [39,45,70]. If developed commercially these devices may be used as aid to *Ayurveda* practitioners, in making primary level prediction prior to his diagnosis and decision.

Although authors have attempted to give an in-depth review of the work in *Nadi Pariksha* and disease diagnosis, the single paper may cover only some of the research world.

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Author contribution

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All authors have read and approved the final version of the manuscript.

Declaration of generative AI in scientific writing

Authors have not used any generative AI tools for this review work.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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