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Review of Traditional Chinese Medicine Pulse Diagnosis Quantification

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1. Introduction

Traditional Chinese medicine (tcm) pulse diagnosis is one of the four major assessments in tcm consultation. Through pulse palpation at three locations, i.e. cun, guan and chi, on both wrists, general health condition of a person and a particular organ can be fully recognized. Figure 1 illustrates the locations and their corresponding organs. tcm doctor is used to combine clinical data collected from pulse assessment and other clinical assessments to prescribe treatments to his patient and monitor his prognosis.
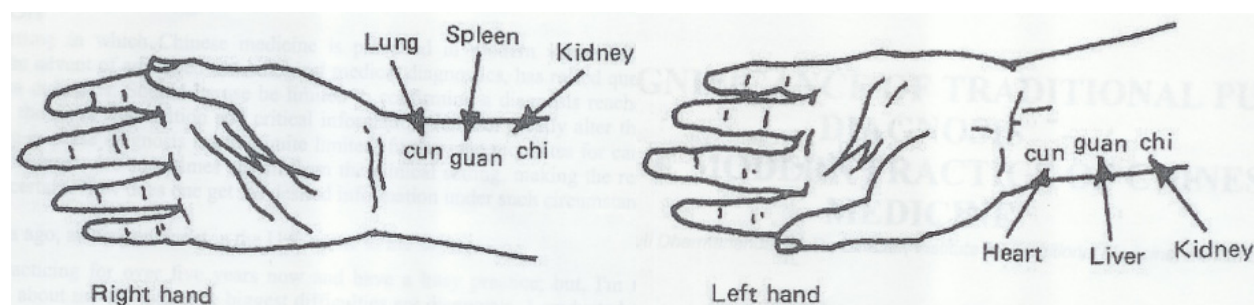

Figure 1. Distribution of organs at the six locations (Adapted from [1])

In view of the increasing popularity of tcm world wide, tcm pulse diagnosis has received much attention from the public concerning its scientific and clinical values. Much research work has been published since 1950s' to quantify tcm pulse diagnosis which aims at providing scientific base to tcm pulse diagnosis and so substantiating its clinical value. The aim of this review is to provide readers with a complete picture of current progression of tcm pulse quantification.

After reading this chapter, readers should be able to

1.   acquire up-to-date scientific evidence on tcm pulse diagnosis quantification;

2. analyze strengths and weaknesses of current studies in terms of methodologies and statistical approaches; and

3. highlight future direction of tcm pulse diagnosis quantification.

The review is divided into five sections. The first three sections discuss and analyze qualification and quantification of tcm pulse diagnosis in ancient and recent literatures. Statistical approaches to quantify tcm pulse diagnosis are discussed. Section four presents a tcm pulse diagnostic framework proposed by the author in 2010 to illustrate the interrelationship of pulse conditions and arterial pulse. The last section highlights limitations of current studies and recommendations are suggested accordingly.

2. Qualification of tcm pulse diagnosis

Qualification of tcm pulse diagnosis means the elements that tcm pulse diagnosis should be included in order to have a complete and valid assessment on tcm pulse. Literatures show that there is much confusion about the assessment of pulse in tcm, mainly due to the ambiguous descriptions of pulse condition in Chinese medical texts [1].

Pulse itself is objective, but pulse condition is subjective. It is the quality of pulse as felt by a tcm doctor, and thus represents the subjective judgment of that doctor. More than 30 pulse conditions have been documented in Chinese medical texts. Some of them, e.g. floating, rapid, string-like are single pulse condition which describes one element of a pulse condition. Others describe more than one element of a pulse condition which is called compound pulse condition. For example, replete is the composite of forceful, long, large and stiff [2].

2.1. Description of pulse condition in ancient Chinese medical texts

Nei Jing [3] describes over 30 types, e.g. large, small, long, short, slippery, rough, sunken, slow, rapid, strong, tough, soft, moderate, hurried, vacuous, replete, scattered, intermittent, fine, and weak. Mai Jing [4] documents 24 types which are floating, sunken, hollow, large, small, skipping, tight, rapid, stirred, slippery, weak, string-like, faint, soft, dissipated, moderate, slow, bound, drumskin, replete, intermittent, vacuous, rough and hidden. The 28 pulse conditions most commonly used in clinical practice come from Bin Hu Mai Xue [5] and Zhen Jia Zhen Gyan [6]. They are floating, sunken, slow, rapid, surging, fine, vacuous, replete, long, short, slippery, rough, string-like, tight, soggy, moderate, faint, weak, dissipated, hollow, drumskin, firm, hidden, stirred, intermittent, bound, skipping, and racing.

Descriptions of pulse conditions in Chinese medical texts are mostly qualitative, and are often illustrated by similes and poems. For instance, the slippery is compared to "beads rolling" and the string-like is like pressing the string of a musical instrument [5]. A few of the descriptions, such as the rapid, the slow, the floating, and the sunken, are quantitative. The rapid and the slow describe the rate of a pulse, and can be quantified by the number of beats per breath. The floating and the sunken describe the depth of a pulse, and can be

quantified by shu, the unit of weight used during the Warring States period (403-221BC) of ancient China, with floating corresponding to three shu and sunken nine shu [7].

Using analogies and poems to describe pulse condition is subject to the interpretation of the tcm doctor. For example, the string-like may be described as like pressing the string of a musical instrument and the tight as like pressing a rope, but the feeling of a string or a rope depends on the sensitivity of one's fingers. Qualifying words such as "a bit," "average," and "very" are used to describe the intensity of a pulse. For example, the difference between the fine and the faint is that the fine is a little bit stronger than the faint. "A little" is countable, but cannot precisely determine how much of this "little" differentiates the fine from the faint.

Descriptions of pulse conditions also overlap [8,9]. Some pulse conditions describe a single dimension of pulse. The floating, for example, describes the depth of a pulse, whereas the rapid describes the rate of a pulse. Others describe two or more dimensions. The firm means string-like, long, replete, surging, and sunken, whereas the drumskin is string-like, large, rapid, and hollow. The number of dimensions that a pulse assessment should encompass is controversial. Floating or sunken and slow or rapid are the two pairs of dimensions suggested in Bin Hu Mai Xue [5]. Nan Jing [7] and Mai Jing [4], in contrast, proposed three dimensions: floating or sunken, slippery or rough, and long or short. Nei Jing [3] described three dimensions: slippery or rough, slow or rapid, and surging or fine, whereas [2] suggested floating or sunken, slow or rapid, and vacuous or replete.

It is suggested that there are two reasons for the obscurity of descriptions of pulse condition. First, tcm doctors are accustomed to assessing pulse by their own perception, rather than on a rational basis [10]. Second, there are no concise and precise standards to guide tcm doctors in the diagnosis of pulse condition. It is likely that these two reasons are the causes of the low inter-rater and intra-rater reliability of pulse diagnosis by tcm doctors found by Craddock (1997) and Krass (1990) (as cited in [11]). As evidence-based practice emphasizes consistency of outcome [12], the low reliability of pulse diagnosis by tcm doctors reported in the literature demonstrates the need to standardize pulse diagnosis in tcm.

2.2. Eight elements: Milestone for standardizing tcm pulse diagnosis qualification

Zhou Xuehai's (1856-1906) early attempt to standardize pulse condition is a milestone in the quantification of tcm pulse diagnosis. He proposed that each pulse condition should have four elements. "Wei Shu Xing Shi Zhe, Zheng Mai Zhi Ti Wang. Qiu Ming Mai Li Zhe, Xu Xian Jiang Wei Shu Xing Shi Jiang De Zhen Qie, Ge Zhong Mai Xiang Liao Ran, Bu Bi Ju Ni Mai Ming" (as cited in [13], p. 31). He explicitly stated that position, frequency, shape, and trend are the four main elements of pulse condition, and that each pulse condition description should contain these four elements.

Various scholars have elaborated on this idea [2,14-18], and have extended the original four elements to eight: depth, rate, regularity, width, length, smoothness, stiffness, and strength.

Each pulse condition should contain these eight elements with different intensities [2,15,17,18].

Rate is the number of beats per breath. The definition of regularity is similar to that in modern medicine, it describes rhythm of a pulse condition. Rate and regularity gives information on the nature of a disease, whether heat or cold [19]. Depth is defined as the vertical position of a pulse, and indicates the location of a disease, whether interior or exterior [19]. Width and length describe the shape of a pulse, where width is defined as the intensity of a pulsation and length is defined as the range in which the pulsation can be sensed across the cun, guan, and chi [2]. Smoothness is defined as the slickness of a pulse, stiffness is defined as the sensation of arterial elasticity, and strength is defined as the change in forcefulness of a pulse in response to a change of applied pressure [19]. Width, length, smoothness, stiffness, and strength also describe the interaction of a pathogen and healthy qi in the body [2]. The eight elements thus provide a basis for qualifying pulse condition.

2.3. Recent works on qualifying tcm pulse diagnosis

King et al. (2002) [11] developed a measurement scale to standardize tcm pulse diagnosis. However, their scale does not reflect pulse condition adequately for several reasons. First, the six items included in the scale –depth, width, force, relative force, rhythm, and pulse occlusion –are not widely accepted as core items in tcm pulse diagnosis. Appropriate rating scales should include the six locations, as a complete tcm pulse diagnosis must include the eight elements at the six locations. Second, the definitions of the items are abstract. For example, force is defined as the overall intensity of a pulse and relative force is defined as a subtler version with overall force. Third, the scale is an ordinal scale that is anchored with descriptors to measure the items. For example, depth is measured at three levels: superficial, middle, and deep. However, an ordinal scale is not a sufficiently sensitive measure, as there are an insufficient number of available response categories to rate the items [20], and the words used to describe each ordinal level are not universal. Further, as the items have not been well quantified, using an ordinal scale would not reflect the actual sensation perceived by a tcm doctor.

To explore the uniqueness of each of the eight elements in tcm pulse diagnosis, Tang (2010) [21] used principal component analysis to explore the uniqueness of each of the eight elements in tcm pulse diagnosis. The result demonstrated that rate, regularity, width and smoothness represented four unique dimensions while it was not the case for depth, length, stiffness and strength.

The author believes that an appropriate content and rating scale must be chosen to measure pulse condition which should be relevant and should adhere to the fundamental concepts of pulse diagnosis in tcm. Since only a handful of studies have been conducted to qualify pulse condition, a rating scale which can genuinely reflect the sensation of pulse perceived by a tcm doctor should be used to minimize the influence of subjective judgment on a rating scale at a preliminary stage of qualification.

3. Quantification of tcm pulse diagnosis

In the qualification of pulse condition, the eight elements are measured unidimensionally. It is hypothesized that the eight elements are related to the arterial pressure waveform and that their intensity is a composite of the physical parameters of the arterial pressure waveform. Relating the eight elements to these physical parameters would thus make them quantitively measurable. Much research has been carried out on the quantification of pulse condition. Measurement of the arterial pressure waveform in the time domain and frequency domain are the two main approaches currently used, but due to the disparity of research aims, methodologies, and statistical approaches, the results of existing studies in this area are incomparable.

3.1. Time domain

The time domain is widely used in cardiovascular research [22] and is also popularly used in the quantification of pulse condition [23]. Time domain analysis looks at the arterial pressure waveform with respect to time, and a time domain graph shows how the arterial pressure waveform changes over time. Figure 2 shows a typical arterial pressure waveform.
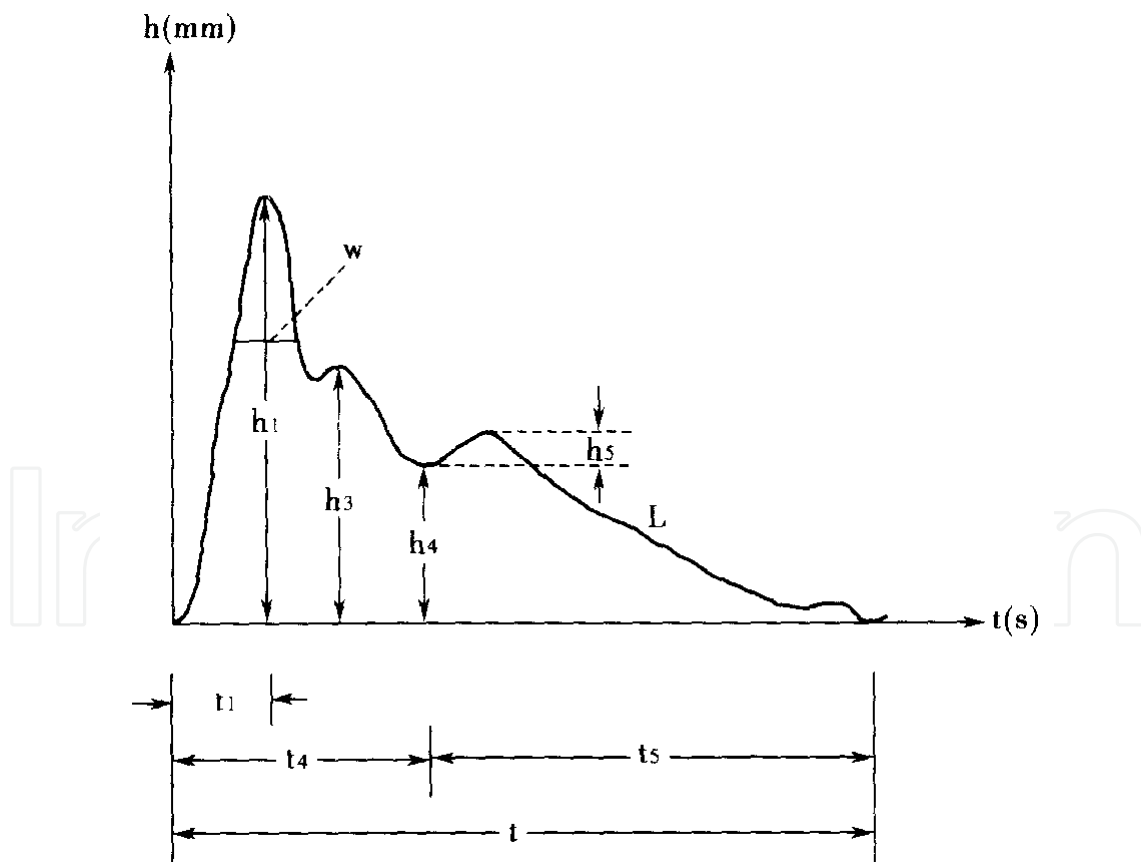

Figure 2. A typical arterial pressure waveform (Adapted from [2], p.163)

In time domain, researchers extracted physical parameters from the arterial pressure waveform, such as h_1, h_3, and generate new parameters from them. Yoon et al. (2000) [24]

proposed three parameters to measure depth, width, and strength. Depth was measured by the hold-down pressure with the relatively largest h_1 (Pamax). The maximum average h_1 (h_1) was used to quantify width, and strength was measured by the pressure difference at the 80% maximum average h_1 ($\Delta80\%$pamax). These three parameters have gained some acceptance as standard parameters for the measurement of depth, width, and strength [2,14].

The advantage of using the time domain for the quantification of pulse condition is that most of the physical parameters related to it have physiological meanings. Exploring their relationship with the eight elements should thus help to understand the elements from a modern medical perspective.

Many studies have demonstrated the association between the physical parameters of the arterial pressure waveform in time domain and the eight elements [2,13,24-31]. Depth has been associated with pamax, rate with t, and regularity with the interval between two individual arterial pressure waveforms and the consistency of the contour of the waveforms. Width has been associated with h_4/h_1, t_1, and h_1. The surging has been found to have a smaller h_4/h_1 and t_1 and a larger h_1. Length has been associated with h_1 at cun, guan, and chi. The short was observed to have small h_1, although association with the other physical parameters in the arterial pressure waveform was indiscernible. Smoothness has been related to W/t, h_4/h_1, t_1, h_5, and h_5/h_1. A smaller h_4/h_1 and a larger h_5 have been observed for the slippery, and h_3/h_1, h_4/h_1, and h_5/h_1 are associated with stiffness. A larger h_3/h_1 and h_4/h_1, and a smaller h_5/h_1 have been observed for the string-like. Four types of arterial pressure waveform have been identified for the string-like: lower h_1 than h_3, h_3 equal to h_1, h_3 higher than h_1, and h_3 merged with h_1. Strength is associated with a $\Delta80\%$ pamax. Some of these observations have been explained in terms of hemodynamic, For example, the string-like was found to be caused by an increase in arterial stiffness and peripheral resistance, whereas width was determined by blood velocity, cardiac output, peripheral resistance, the diameter of the radial artery, and the spatial movement of the radial artery. Length has been related to the rate of arterial dilatation.

The incongruence of the results of these studies means that their postulations cannot be substantiated. Fei (2003) [2] reported that the superficial and deep levels of depth ranged from 25 to 175g and 100 to 250g, respectively. According to Xu et al. (2003) [27], the range of the superficial, middle, and deep levels was smaller than 100g, 100-200g, and greater than 200g, respectively. In these studies, depth is reported as a unit of force, whereas in other studies report as a unit of pressure [25,26]. Huang and Sun (1995) [26] reported that the superficial, middle, and deep levels ranged from 10 to 40 mmHg, from 50 to 80 mmHg, and 90-120 mmHg respectively, whereas Chen (2008) [25] reported ranges of 89.8 to 157.7 mmHg, 151.9 to 222.9 mmHg, and 279.3 mmHg for the superficial, middle, and deep levels, respectively. In terms of smoothness, Huang and Sun (1995) [26] characterized the slippery as having t_1 within the range of 0.07 to 0.09s, h_5 larger than 2 mm, obvious h_3, and h_4/h_1 smaller than 0.50, whereas Fei (2003) [2] found that the slippery was characterized as having W/t smaller than 0.20, an h_4/h_1 smaller than 0.40, and h_5/h_1 larger than 0.10.

There appear to be four reasons for such inconsistency. First, none of the studies reports the surface area of the sensor used. As force varies with the surface area of a sensor with the same hold-down pressure, the lack of this information makes the results incomparable. Second, the characteristics of the subjects in the studies may have affected the results. Age, gender, and weight are all factors that affect pulse condition [2,26], yet these studies report no demographic data on the subjects. Hence, it is not possible to rule out that the incongruence is due to the diversity of the subjects. Third, there is no protocol that standardizes the pulse acquisition procedure, and few of the studies reported the procedure that they used to acquire the waveform. To mimic a tcm pulse assessment, the arterial pressure waveform is acquired with different hold-down pressure applied to the radial artery. Two procedures for pulse acquisition are known. Huang (2007) [13] developed a formula to calculate how much hold-down pressure should be used for the superficial, middle, deep, and hidden levels of depth in women and men. He also proposed that the ratio of actual body weight over ideal body weight is the determinant of the hold-down pressure (Table 1).

(Actual weight)/(Ideal weight)	Hold-down Pressure at Different Levels of Depth			
	Superficial	Middle	Deep	Hidden
< 0.8	50g	100g	200g	300g
0.8 – 1.0	70g	130g	250g	400g
1.0 – 1.2	100g	180g	300g	450g
> 1.2	150g	230g	350g	550g

Table 1. Weight ratio and corresponding hold-down pressure

Although several studies have adopted this protocol to acquire the waveform [28,32,33], the rationale for quantifying depth in this way is not explicated, and its credibility is thus suspect. The other procedure is that of Fei (2003) [2], who applied pressure from 0 g to 250 g at 50g intervals for each pulse acquisition. However, the interval of 50 g may be too wide, and does not allow for any change in the waveform within this interval.

Fourth, there is no standard measurement for the eight elements. The majority of the aforementioned studies focused on pulse condition rather than the eight elements. However, as each pulse condition embraces all eight elements with different intensities, even if the other seven elements have the same intensity, variation in one element will lead to a different waveform for the same pulse condition. Moreover, the sensation of a tcm doctor to the eight elements has not been standardized, and variation among the tcm doctors participating in the studies will inevitably have led to different results.

3.2. Frequency domain

The frequency domain can be used to analyze pulse condition based on the energy distribution of the arterial pressure waveform [34]. A frequency domain graph comprises

two parts –amplitude versus frequency and phase versus frequency – and is converted from the time domain of the arterial pressure waveform using a transform, which is a pair of mathematical operators used to carry out a conversion. Fast Fourier transform is an example of a commonly used transform in signal processing. Usually, the amplitude versus frequency graph is examined in studies of pulse condition. A graph showing only the amplitude and frequency is called a power spectrum (Figure 3).
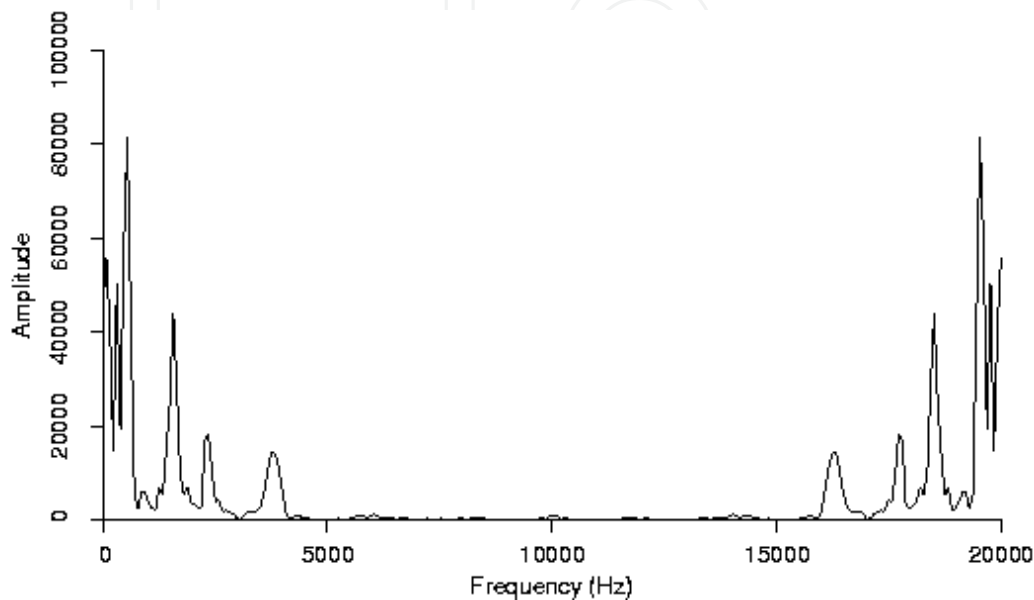

Figure 3. Example of a power spectrum (Adapted from [34])

The y-axis of a power spectrum graph, which is labelled "amplitude" represents the power of the frequency, whereas the x-axis shows the "frequency" in Hertz (Hz). A harmonic is the frequency component of an arterial pressure waveform.

The majority of the studies that use the frequency domain to analyze the arterial pulse have focused on differentiating diseases [35-37], examining the power spectrum in relation to the meridians [38,39], and investigating the relationship among disease, syndrome, and channels [23,40-43,45]. Only a few studies have explored the characteristics of the power spectrum for different pulse conditions [46,47].

Wang and Xiang (1998) [46] discovered that the power spectrum differed markedly for the normal, the slippery, the string-like, and the slow-intermittent. In general, the power spectrum of all pulse conditions decreased with increasing frequency and the frequency range was within 0 to 40Hz. However, the power spectrum of the normal was smoother than that of the other three pulse conditions. The slippery had more than ten harmonics, whereas the normal had eight harmonics. The string-like and the slow-intermittent had three to five harmonics. The frequency of the normal was distributed within the 25Hz range. The percentage of energy distributed below 10Hz was 99% for the normal and 97% for the string-like, and that distributed below 5Hz was 90.2% for the moderate, 83.7% for the slippery, and 60.9% for the string-like. Forty-five percent of the energy was distributed below 1 Hz for the moderate and 16% for the string-like. These findings suggest that the

frequency of the normal falls within the 1 to 5Hz range, and those frequencies below 1 Hz and over 10 Hz may indicate illness. Xu et al. (2002) [47] suggested that counting the number of harmonics in the power spectrum could be used to differentiate pulse conditions. Their study reported that the slippery possessed three main harmonics that were much higher than those of the normal, and the drumskin had two main harmonics. The amplitude of the harmonics in the normal decreased with increasing frequency. The reasons for the different results for the slippery are the same as those proposed for the time domain quantification.

Both the time domain and frequency domain are based on the arterial pressure waveform, but differ in the way in which they interpret it. Although the available evidence supporting the applicability of the frequency domain to quantify pulse condition is weaker than that supporting the use of the time domain, this may simply due be to the lack of studies on the frequency domain. However, the time domain is to a certain extent more advantageous than the frequency domain for quantifying pulse condition because the physical parameters in the time domain have physiological meanings, which means that the physiological implications of the eight elements could be revealed if their relationship with these physical parameters were traced. It is thus more prudent and beneficial to adopt the time domain in the quantification of pulse condition.

4. Statistical approaches

Though regression analysis is commonly used in medical research for function approximation and classification [48,49], failure of modelling the relationship of the eight elements and the physical parameters [21] suggested that the relationship is not linear. It has been suggested that more advanced statistical techniques, such as fuzzy inference and artificial neural network (ANN) may be more appropriate for modelling the relationship of the eight elements at the six locations and the physical parameters [50-52].

Fuzzy inference is a modelling technique that is based on fuzzy set theory. Fuzzy set theory deals with the degree of truth in a vaguely defined set, where truth is represented as a value that ranges from 0 to 1. Lee et al. (1993) [53] used fuzzy inference to assess the health state of a subject with renal problems before and after taking herbal medicine. The arterial pressure waveform was acquired at the right chi, and the physical parameters in the time domain were used to construct the fuzzy model. The results showed that the model could successfully predict the prognosis for a patient. The authors thus proposed applying fuzzy inference to assess health status using pulse condition.

ANN is a nonlinear statistical modelling technique commonly used in the modelling of complex nonlinear relationships among independent variables and dependent variables [49,54]. It resembles regression analysis, but has much more flexibility because it is not restricted by any statistical assumptions or prespecified algorithms. In other words, ANN is a self-adaptive and data-driven modelling technique [54,55]. The presence of hidden layers in the network greatly increases its capacity to deal with various complicated relationship. Figure 4 shows the basic architecture of an ANN.
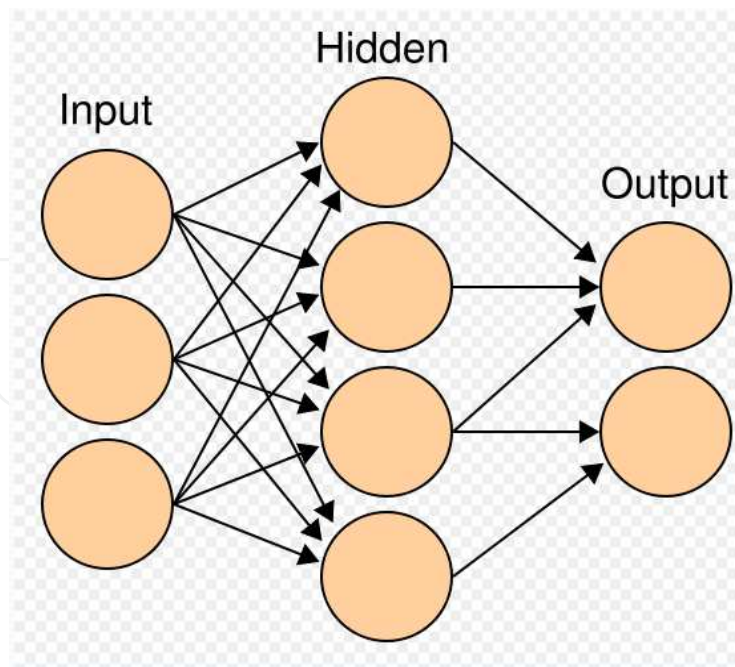
Figure 4. Basic architecture of an ANN (Adapted from [56])

The architecture shown in Figure 4 is commonly used in the type of ANN known as a multilayer perceptron. This consists of an input layer, a hidden layer, and an output layer. The input layer and output layer also appear in the architecture of linear regression, but the distinguishing characteristic of an ANN is the hidden layer in between the input and output layers. The number of hidden layers can be manipulated by the researcher until a satisfactory result is obtained. The input layer contains input neurons, which represent the number of independent variables in the study. The output neurons in the output layer are the dependent variables. The number of hidden neurons in the hidden layer(s) and the number of hidden layers in the model are determined by trial and error using the sum-squared error in function approximation and the cross entropy function in classification. The cross entropy function can be regarded as analogous to the likelihood function in logistic regression [54]. They are the cost functions that determine when to stop training the model.

Backpropagation is the most popular training algorithm for ANNs. This utilizes the steepest gradient descent in a multilayer perceptron to minimize the sum-squared error. The steepest gradient descent is a mathematical algorithm that locates the local minimum of a function by taking steps proportional to the negative of the gradient of the function at the current point. In backpropagation, the weights of the hidden and input neurons are modified according to the sum-squared error fed back from the output neurons until the mean squared error is minimized.

Wang and Xiang (2001) [57] compared the accuracy of fuzzy inference and ANN in predicting pulse condition. They reported the successful application of ANN in identifying the normal, the string-like, the slippery, and the fine, and showed that ANN had a 87% predictive accuracy, which was 12% higher than that of fuzzy inference. Xu et al. (2007) [58] compared the predictive accuracy of traditional ANN and fuzzy neural network in predicting eight pulse conditions. Three traditional ANNs using backpropagation were

developed, each of which had 3 layers: an input layer, a hidden layer, and an output layer. The input neurons were seventeen physical parameters of the arterial pressure waveform in the time domain and the output neurons were the eight pulse conditions, which were, however, not specified. The numbers of hidden neurons used in the three traditional ANNs were 10, 15, and 20. The fuzzy neural network was a composite of four sub-fuzzy neural networks, and was used to model seventeen physical parameters and the four elements (position, frequency, shape and trend) proposed by Zhou Xuehai (1856-1906) (as cited in [13]) separately. The four sub-fuzzy neural networks were then combined to predict the eight pulse conditions. The three traditional ANNs obtained 86-88% accuracy, but the fuzzy neural network outperformed these networks by 4%. They concluded that it was beneficial to combine fuzzy inference and ANN to quantify pulse conditions.

The successful application of these advanced statistical techniques for quantifying pulse conditions is encouraging, and at least indicates that the various pulse conditions have a physiological basis. However, medical research emphasizes the explanatory power of a model, and values statistical techniques with a high explanatory power [59-61]. According to these criteria, ANN can be condemned as black box [49], which means that the internal knowledge of the system cannot be readily known by researchers [59].

5. tcm pulse diagnostic framework: Integration of the East and the West

A dice model has been formulated by Tang (2010) [21] to explain the interconnection and interrelation between the arterial pulse and the eight elements of pulse condition at the six locations, and between the eight elements at the six locations and health status in tcm. This framework serves as the backbone to quantify tcm pulse diagnosis.

The dice model comprises two levels. Level one includes the arterial pulse and the eight elements at the six locations, and level two covers the eight elements at the six locations and health status in tcm. More specifically, level one deals with the sensation of the arterial pulse as perceived by a tcm doctor, and level two gives an interpretation of the eight elements at the six locations to determine health status. These two concepts are interconnected. The symbolic meaning of a dice and a dice roll with respect to the arterial pulse and the health status in tcm are explicated below.

5.1. Arterial pulse and the eight elements at the six locations

It is postulated that the eight elements are influenced by the arterial pulse at the six locations (left and right cun, guan, and chi). Depth, rate, regularity, width, length, smoothness, stiffness, and strength are the eight elements of pulse condition at the six locations. The intensity of each element is determined by the sensation of the arterial pulse perceived by a tcm doctor. Thus, the eight elements at the six locations are operationalized as a rating along a continuum with Yin and Yang at the extremes.

Specifically, depth is operationalized as the vertical position of the arterial pulse, and is rated along a continuum with the deepest being Yin and the most floating being Yang.

Rate is the number of beats in a minute, with the slowest being Yin and the most rapid being Yang. Regularity is the rhythm of the arterial pulse, which is categorized as either regular or irregular. Width is the intensity of the arterial pulse, with the smallest being Yin and the largest being Yang. Length is the range of the arterial pulse that can be sensed across cun, guan, and chi, with the shortest being Yin and the longest being Yang. Smoothness is the slickness of the arterial pulse, where the roughest is Yin and the smoothest is Yang. Stiffness is the elasticity of the radial artery, with the least stiff being Yin and the stiffest being Yang. Finally, strength is the forcefulness of the arterial pulse relative to the change in pressure applied by a tcm doctor, with the least forceful being Yin and the most forceful being Yang.

5.2. The eight elements at the six locations and health status

In tcm pulse diagnosis, health status is determined by the pulse condition at the six locations, with each location reflecting the health status of a specific organ. Left cun, guan, and chi reflect the health status of the heart, the liver, and the kidneys, whereas right cun, guan, and chi reflect the health status of the lungs, the spleen, and the kidneys (lifegate). The eight elements are the assessment criteria for the health status of the organs. Health status is the outcome measure of tcm pulse diagnosis, and is a composite measure of the health status of the organs.

5.3. The dice model

In the model, a dice is used to embody the intertwining and cascading relationship among the arterial pulse, the eight elements at the six locations, and health status (Figure 5). Figure 5 shows a diagrammatic presentation of the dice model.

5.3.1. Assumptions

The dice model is formulated under three assumptions. The first is that the eight elements carry the same weight in the assessment of overall pulse condition. Second, the mid-point along a continuum indicates the balance of Yin and Yang. Third, the six locations have the same weight in determining health status.

5.3.2. Symbolic meaning

The dice is analogous to the concept of health in tcm. Health is perceived as the balance of Yin and Yang, which in turn relies on the individual functioning and interaction of the organs. The six pyramids that make up a dice are thus analogous to the organs at the six locations.

The inside of the dice represents the blood flow within the organs, the combination of which constitutes the arterial pulse. Hence, any change in the blood flow from any of the organs is reflected in the arterial pulse. By assessing the six pyramids, the health status of the organs and thus overall health status can be revealed.
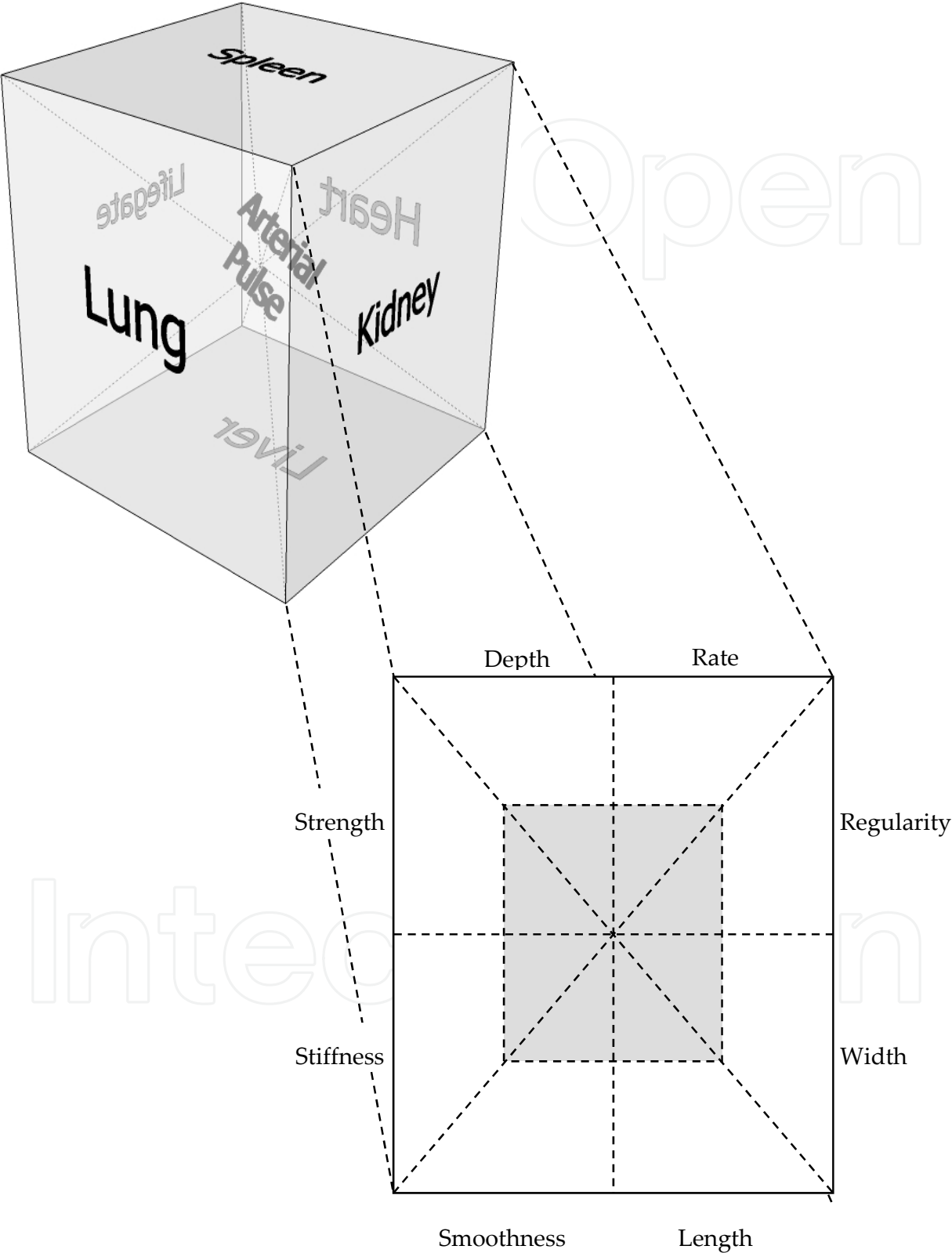
Figure 5. The dice model

5.3.3. Position of the six organs

As has been stated, the six pyramids represent the six locations where the pulse is assessed by a tcm doctor. The lungs and the heart, the liver and the spleen, the kidneys and the lifegate are arranged in opposite pyramids according to their role in overall health. This arrangement is based on the notion that left cun, guan, and chi assess the blood, which is Yin in nature, whereas right cun, guan, and chi assess qi, which is Yang in nature. The position of the organs arranged in the dice thus adheres to Yin Yang theory.

5.3.4. The eight elements

Each pyramid is made up of the eight elements. The enlarged square to the lower right of Figure 5 shows the interrelation of the eight elements. Each element is a complementary Yin-Yang pair. According to Yin Yang theory, Yin always represents the inside and Yang the outside. Thus, the black square indicating the Yin nature of the elements is the core of the pyramid, and the white square indicating their Yang nature is the outer part of the pyramid.

The intensity of the eight elements depends on the arterial pulse. The combined intensity of the eight elements thus indicates the health status of the organ denoted by that pyramid.

5.3.5. Interconnection in the dice model

The dice model of tcm pulse diagnosis is inspired by the Taiji symbol. The dotted line that links the six pyramids together symbolizes the interchanging and dynamic relationship among the organs. In the model, the Yin and Yang of each element, the eight elements in each pyramids, and the six pyramids of the dice are connected with dotted lines, which means that they are Yin and Yang composites and are always interchanging and balancing one another. The solid outline of the dice represents the absolute of health, just as the Taiji circle represents the world. Health is not expandable or reducible: it is only the health status that can be altered, which is determined by the interaction of Yin and Yang in the body.

5.3.6. Analogy between a dice roll and health status

To further elaborate the dice model, a roll of the dice is taken as analogous to health status. With a balanced or "fair" dice, the probability of rolling each pyramid is equal, because the areas and weights of the pyramids are identical. A "fair" dice is thus analogous to a healthy status, in which the blood flow within the organs is normal, the wave reflection and wave resonance occur in the proper way, the intensity of the eight elements is around the mid-point of the continuum and forms a regular shape in the middle of the pyramid, and the six pyramids are equal and balanced. Yin and Yang are balanced and harmony is attained.

However, if any one of the pyramids is intentionally altered in terms of its area or weight, then the dice is no longer "fair" and can be called a loaded dice. With a loaded dice, the probability of rolling each pyramid is unequal, and varies with the area and weight of the pyramids. A loaded dice is analogous to an unhealthy status, in which the abnormal

functioning of any of the organs affects the wave reflection and wave resonance within the circulatory system, blood flow is altered, and thus the weight of the pyramid representing that organ is altered. The arterial pulse changes in accordance with the health status of the organ, and thus the intensity of the eight elements also changes. The pyramid formed by the eight elements is no longer regular, but is smaller or larger and skewed. An imbalance thus occurs in the six pyramids, Yin and Yang are imbalanced, and health is compromised.

5.4. Recent works on validating the framework

Several works have been done to verify the hypotheses of the framework. Tang et al. (2012) [62] conducted a study to validate the content and diagnostic ability of the framework. Content validation index was 0.73 which was acceptable. And the criterion validation was conducted by comparing the accuracy, sensitivity and specificity of the models generated by artificial neural networks. About 80% accuracy was attained among all ANN models. Their specificity and sensitivity carried, ranging from 70% to nearly 90%. It suggested that the tcm pulse diagnostic framework was valid in terms of its content and diagnostic ability.

Tang et al. (2012) [63] reported that the nonlinear relationship of the eight elements at the six locations and the physical parameters in time domain were successfully established by Levenberg-Marquardt algorithm with an r-squared ranged from 0.60-0.86.

6. Conclusion: What's next?

The tcm pulse diagnostic framework is a novel direction suggested by Tang (2010) [21] to guide tcm pulse diagnostic quantification. Despite studies [62,63] have been conducted to verify the hypotheses in the framework, the results were preliminary and yet verified the framework fully. Much more effort has to be made in the future. This session highlights limitations of the studies and corresponding recommendations are given.

6.1. Limitations

6.1.1. Methodology

tcm doctors usually assess pulse at the six locations both individually and simultaneously. However, pulse acquisition device used was usually a single-probe type, as no validated three-sensor pulse acquisition device is available, and the arterial pressure waveforms could only be acquired one at a time. Thus, the simultaneous manipulation of pulse at the six locations carried out in a typical tcm pulse diagnosis could not be examined.

The pulse acquisition process was fairly long at about one hour as reported by [62], [63], which may have provoked motion artifacts in the subjects that affected the quality of the arterial pressure waveforms acquired. Also, the baseline of the arterial pressure waveform fluctuated due to the movement and breathing pattern of the subjects, and the feature extraction program was insufficiently developed to remove this noise from the waveforms. The rescaling of the fluctuating baseline into a horizon would have distorted the arterial

pressure waveform and introduced errors into the features extracted. One of the physical parameters, peak-to-peak interval, could not be extracted by the program and thus could not be used in the modelling. Further, the pulse acquisition device limited the hold-down pressure to a maximum of 400 mmHg, but the amplitude of the arterial pressure waveform did not decrease in some of the subjects, and thus Δ80%pamax could not be calculated.

Another limitation is about characteristics of the subject recruited. Those subjects recruitment in [62], [63] were rather stable, the intensity of the eight elements was therefore confined to a narrow range, and such homogeneity in the samples may have lowered the r-squared.

6.1.2. Statistical approaches

ANN was suggested to verify the relationships in the framework because of their nonlinear nature. There are several limitations with this approach needed to be overcome. First, the sample size required by the ANN was too large to be recruited in a clinical study, and the smaller sample size used may have lowered the effect size of the models. Second, as mentioned before, the low explanatory power of ANN does not allow researchers to fully analyzing the models generated.

6.2. Recommendations

In view of the limitations of the studies, five recommendations are made for further studies in this area.

6.2.1. Methodology

It is suggested that a validated three-sensor pulse acquisition device be developed so that the effect of simultaneous hold-down pressure on the arterial pressure waveforms at cun, guan, and chi can be examined. Also, the feature extraction program requires further enhancement to extract all of the necessary features from the arterial pressure waveform. The development of the feature extraction program is a major part of the study because the physical parameters are calculated based on the features extracted by the program.

6.2.2. Statistical approaches

A program should be generated that can extract the underlying relationships among the physical parameters and the eight elements at the six locations and the relationships among the eight elements at the six locations and health status. Increasing the explanatory power of the models in this way would provide modern scientific theoretical backing for tcm pulse diagnosis and more evidence to support tcm theories.

Another suggestion is on subject recruitment. More diverse subjects should be recruited to verify the models. The models established are preliminary models that demonstrate the nonlinearity of the physical parameters and the eight elements, but a larger sample is

required to validate them fully. As those studies recruited subjects with stable hypertension, the models cannot be extrapolated to patients with severe hypertension or hypotension. It is thus recommended to recruit subjects with severe hypertension or hypotension in future studies to increase the generalizability of the models. In addition, patients with other diseases should also be recruited to examine the models' ability to differentiate hypertension from other diseases.

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