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Review Article

The meridian system and mechanism of acupuncture—A comparative review. Part 1: The meridian system

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Abstract

In traditional Chinese medicine (TCM), acupuncture has been used to heal various diseases and physiologic malfunctions in clinical practice for more than 2500 years. Due to its efficacy, acupuncture has been recommended by the World Health Organization in 1980 as an effective alternative therapy for 43 different disorders. Over the past few decades, various theories of the meridian system and mechanisms have been proposed to explain how acupuncture might work. Most of these mechanisms, however, cannot yet explain conclusively why acupuncture is efficacious in treating so many different diseases. A plausible mechanism has been unavailable until recently. This is the first of a three-part series that aims to provide a comparative review of the aforementioned topics. Part 1 reviews the current indications for acupuncture, basic concepts of TCM, and the essence of the meridian system. To establish a mathematically rigorous framework of TCM, the *chaotic wave theory of fractal continuum* is proposed. This theory is then applied to characterize the essence of the meridian system. Parts 2 and 3 will review the possible mechanisms of acupuncture analgesia and acupuncture therapies, respectively, based on biochemical, bioelectromagnetic, chaotic wave, and neurophysiologic approaches. It is sincerely hoped that this series of review articles can promote an understanding of the meridian system and acupuncture mechanisms to help patients in a logical and passionate way.

Keywords: acupuncture; chaotic wave theory; fractal continuum; meridian system; TCM

Introduction

Acupuncture is an important and integral part of traditional Chinese medicine (TCM). It has proved itself to be clinically effective for more than 2500 years and remains an energetic and vibrant treatment. It is fair to say that the widespread use of acupuncture in the East and West has helped millions of patients worldwide. This is perhaps one of the main reasons that in 1980, the World Health Organization (WHO) recommended acupuncture as an effective alternative therapy for 43 different disorders. In October of the same year, the WHO Regional Office for the Western Pacific attempted to develop standard international acupuncture nomenclature [1]. Yet, at that time, the list of 43 indications was not based on rigorous clinical trials and its credibility was questioned. Since then, extensive studies on acupuncture have been conducted in controlled clinical trials. Many convincing results have been reported and many important papers have been cited [2].

Due to bias, conflict of interest, misinterpretation, or misunderstanding, however, negative reports about acupuncture are also abundant. For instance, treating hypertension by acupuncture has been criticized as lacking demonstrated efficacy and cost-effectiveness [3,4]. However, the experimental results in the Stop Hypertension with the Acupuncture Research Program (SHARP) are convincing, indicating that acupuncture is efficacious whether or not it is administered according to the standard principles of TCM, as individualized acupuncture, or as invasive sham acupuncture [3]. More surprisingly, 6 weeks of twice-weekly sessions of these three methods of administration can reduce both systolic and diastolic blood pressures for 12 months, as can be seen from Fig. 2 of that study [3]. Unfortunately, those investigators failed to point out the efficacy of acupuncture. Instead, they

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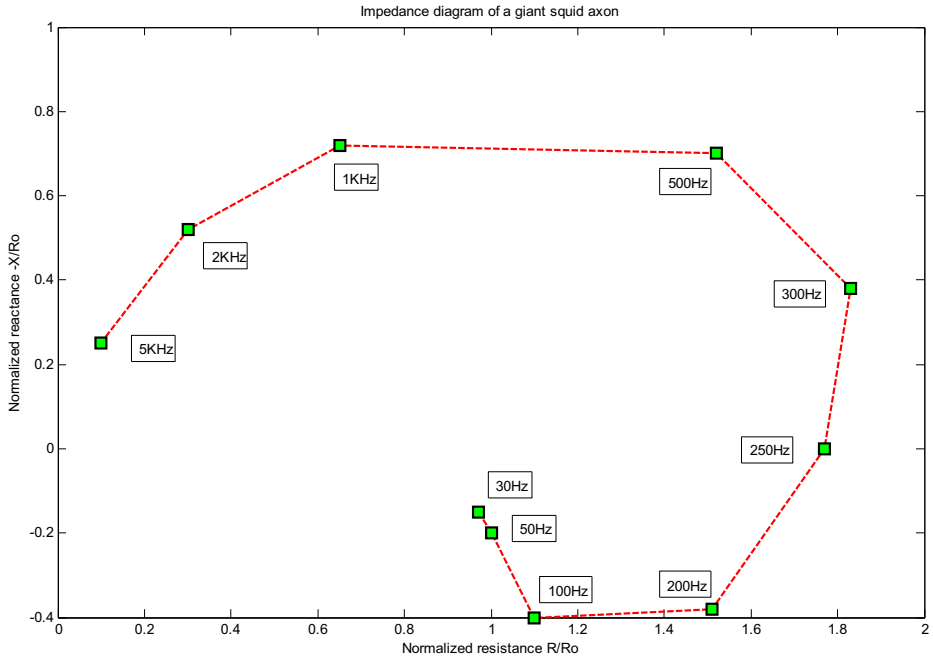

Fig. 1. Longitudinal impedance diagram of the squid giant axon membrane. From "Hypertension: a comparative review based on fractal wave theory of continuum," by S. Chang, 2011, Adapt Med, 3, p. 91–8. Reprinted with permission.

concentrated on making comparisons among these three different yet almost equally effective acupuncture techniques. Because the essence of the meridian system and mechanism of acupuncture were not comprehended, the investigators did not understand why these three methods would all work so well. Consequently, they did not emphasize the efficacy of acupuncture but only contended that the active acupuncture could not be differentiated from invasive sham acupuncture. An obvious case of misunderstanding due to this kind of misinterpretation is exemplified in a 2006 editorial commentary [4]. In the commentary, the editor hastily jumped to the conclusion that "acupuncture is of no value for the treatment of hypertension" [4].

Fortunately, a credible report with almost 300 references on the clinical practice of acupuncture reviewed by the WHO Consultation on Acupuncture has consolidated the position of

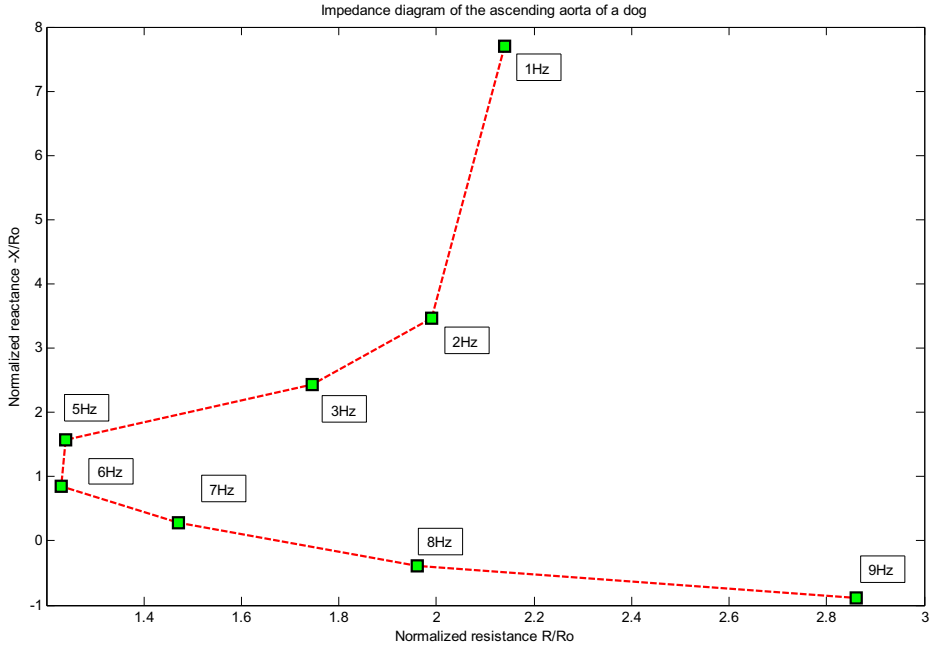

Fig. 2. Input impedance diagram of the ascending aorta of a dog. From "Hypertension: a comparative review based on fractal wave theory of continuum," by S. Chang, 2011 Adapt Med, 3, p. 91–8. Reprinted with permission.

acupuncture as effective [2]. It is imperative, however, to elucidate the characteristic essence of the meridian system and the mechanism of acupuncture so that misinterpretation and misunderstanding can be avoided. Parts 2 and 3 of this three-part series will review acupuncture mechanisms based on biochemical, bioelectromagnetic, chaotic wave, and neurophysiologic approaches in the existing literature. It is necessary, in this article, to clarify that the meridians exist or not before the various mechanisms of acupuncture can be reasonably studied. First, current indications for acupuncture will be presented. Next, to correctly interpret the ancient Chinese meridian system, the *chaotic wave theory of fractal continuum* is proposed to mathematize the basic concepts of TCM. Hence, TCM and in particular acupuncture can be placed on a scientific footing to be studied in the future in terms of modern techniques. The review will proceed to the different theories of the meridian system, and then to the conclusion of Part 1.

Indications for acupuncture

In 1996, a credible report on the clinical practice of acupuncture was reviewed by the WHO Consultation on Acupuncture [2], which indicated that the diseases or disorders for which acupuncture therapy had been tested in controlled clinical trials could be classified into four categories. The first category included 28 different diseases, symptoms, or conditions for which acupuncture had proved to be effective. The second category included 63 of those conditions for which therapeutic effects of acupuncture had been shown but further proof was needed. The third included nine conditions for which acupuncture was worth trying because treatment by conventional and other therapies was difficult. Finally, the fourth included seven conditions for which acupuncture might be tried, provided the practitioner had special modern medical knowledge and adequate monitoring equipment. Consequently, there were more than 100 different diseases or disorders for which acupuncture therapy could be of help to the patients.

To obtain an idea of what acupuncture can do for patients comprising the four different categories as indicated by the WHO, a few diseases or disorders from each of the four categories will be discussed here [2]. In the first category, acupuncture has proved to be effective for allergic rhinitis, the primary dysmenorrhea of gynecologic disorders, depression, dysentery, essential hypertension, primary hypotension, leucopenia, low back pain, rheumatoid arthritis, sciatica, sprain, and stroke. In the second category, acupuncture has proved to have therapeutic effect on alcohol dependence and detoxification, Bell palsy, bronchial asthma, cancer pain, cardiac neurosis, cholelithiasis, craniocerebral injury, diabetes mellitus, female infertility, gouty arthritis, hepatitis B virus carrier status, insomnia, male sexual dysfunction, stiff neck, Tourette syndrome, urolithiasis, and vascular dementia. In the third category, acupuncture can be used for treatment of deafness, hypophrenia, irritable colon syndrome, neuropathic bladder in spinal cord injury, and pulmonary heart disease. In the fourth category, if the practitioner has modern medical knowledge and adequate monitoring equipment, acupuncture may be helpful in the treatment of breathlessness in chronic obstructive pulmonary disease, coma, convulsions in infants, coronary heart disease (angina pectoris), diarrhea in infants and young children, and viral encephalitis in children.

The aforementioned clinical evaluations have indicated that acupuncture is effective in the treatment of various diseases and physiologic malfunctions. From the efficacy viewpoint of acupuncture, it is clearly a nonspecific therapy that can handle a broad spectrum of indications. Any plausible mechanism of acupuncture proposed has to be able to explain how it works not only for just one condition, but also for all or at least most of the diseases and disorders. To date, most of the studies on acupuncture mechanism have concentrated on explaining the actions of acupuncture concerning analgesia, or just one specific type of physiologic malfunction [5–28]. This is not good enough even though explanation of the actions of acupuncture concerning analgesia is already quite difficult. To understand exactly how acupuncture works in clinical practice for so many different diseases, it is important to first comprehend the basic concepts of TCM.

Basic concepts of TCM

It is well known that the basic concepts of TCM are derived from ancient Chinese natural philosophy. In this section, it will be shown that the fundamental philosophical concepts of *chi*(*qi*), *yin-yang*, and *five-phases* can be mathematized in terms of modern dynamic systems [29–31]. Then, these basic concepts will be applied to TCM and acupuncture.

The natural philosophy of space and time in the ancient Chinese agrarian society was derived from the interaction of cyclic motions of several celestial bodies. For instance, Chinese lunisolar calendars were devised to reconcile the incommensurability of the *periods* involving the relative motions of the sun, moon, and earth. In concert with our planet, the circadian, monthly, and seasonal rhythms were discovered. In addition to the celestial long cycles, short physiologic rhythms in humans were also noticed. For instance, heartbeat, radial arterial pulse, respiration, and bladder contraction during micturition were also ubiquitous in daily life [32–39]. These rhythms usually interact among themselves and with the outside environment. Hence, ancient Chinese natural philosophy and TCM were focused mainly on the collective interactions of various *periodic* motions at the outset. It is understandable that, due to lack of mathematical machinery, the quantitative description of rhythmic interactions was impossible in ancient times. As a substitute, terse qualitative terms were invented to describe the complex behavior of dynamic systems. For instance, terms and concepts such as *qi*, *yin-yang*, and *five-phases* were invoked more than 3000 years ago to fill the gap between theory and practice.

To put the concepts of *qi, yin-yang*, and *five-phases* in terms of the language of modern dynamic systems, the archaic meaning of *qi* will be examined first [29–31]. This Chinese

character was originally a pictogram of the water that evaporates and becomes clouds. Hence, *qi* referred to part of the dynamic water cycle. In terms of modern scientific language, *qi* stands for the fractal continua of vapor and water, and the complex dynamics of phase change in the water cycle. Without loss of generality, we can define qi as a mathematical dynamic system that is characterized by a triple (M, μ, Φ_t), where M denotes either a compact manifold or fractal continuum that can represent, for instance, the water, air, material, or the collection of state variables describing that material. For instance, the amplitudes, frequencies, or phases of periodic motions are some of the options for the state variables. Here, μ denotes a measure on M, and Φ_t: $M \to M$ a one-parameter group of continuous, measure-preserving transformation on M. The mapping Φ_t is used to denote the dynamic behavior on M. The parameter t could be a real number or an integer depending on our observation or experimental setup. When it is an integer and generated by a fixed map Φ, the dynamic system will be discrete and can be denoted as (M, μ, Φ).

The ancient meaning of yin-yang was actually referring to two fundamental operations in the universe or a dynamic system, now one dominating, now the other, in a wavelike succession [40,41]. Hence, they could be modeled by a pair of sinusoidal functions with a relative phase difference. If the relative phase difference is 90 degrees and these two functions are perpendicular, then they will form a periodic orbit in the two-dimensional state space. Another way to represent the idea of yin-yang is to use a hyperbolic operator Φ on the phase space (M, μ, Φ). For instance, a well-known and important example is the phase-lead and phase-lag operator in the phase space. To describe it mathematically, M can be denoted as a torus: $\{(x,y)(mod\ 1)\}$, i.e., the phase space of two interacting or competing rhythms with measure $\mu = dxdy$, and the hyperbolic yin-yang operator can be denoted as $\Phi(x,y) = (2x + y, x + y)(\mathrm{mod}\ 1)$.

Finally, the idea of five-phases can be defined as the Markov partition of the previous torus M by the yin-yang hyperbolic map $\Phi(x,y) = (2x + y, x + y)(\mathrm{mod}\ 1)$. This hyperbolic flow Φ is also topologically semiconjugated to the subshift of finite type determined by the transition matrix

$$A = \begin{bmatrix} 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

Hence, the hyperbolic map Φ of yin-yang can generate five-phases as a Markov partition of the phase space M. The symbolic dynamics associated with A, a subshift of finite types, is very useful and at the same time very interesting. For instance, the dense periodic orbits, topologic transitivity, ergodicity, and mixing of the dynamic systems can be studied [29–31]. Furthermore, the transition matrix A can generate admissible trajectories in terms of symbolic dynamics. In case the initial frequencies of two interacting or competing rhythms are incommensurable, then their corresponding phase trajectories as functions of time will trace out a dense orbit in the phase space M, the first hallmark of chaotic wave theory. In addition, the set of functions $\{e^{2\pi i(px + qy)}\}$ where p and q are integers is an orthonormal basis of $L^2(M,\mu)$. The collective effects of various rhythms can be defined formally as an infinite series of wave oscillations with random amplitudes $\sum_{n=-\infty}^{\infty} \xi_n e^{2\pi i n x}$where $\{\xi_n\}$is a sequence of independent, identically distributed standard gaussian random variables. Notice that this infinite sum will not converge, but if it is integrated over a period of time, the integral $B(t) = \int_0^t \sum_{n=-\infty}^{\infty} \xi_n e^{2\pi i n x} dx$ will converge almost surely and in the L^2sense. This random Fourier series of a countable infinite number of dense waves is the second important hallmark of *chaotic wave theory.*

Once the ancient philosophical ideas of *qi, yin-yang*, and *five-phases* have been equated with concepts in the *chaotic dynamical system*, they can readily be applied to TCM. It is noteworthy in TCM, however, that physiology is more important than anatomy, or function is more important than structure. The rationale behind this philosophy of TCM is that physiologic functions can always *adapt* even when the structure or morphology changes a little. Consequently, in TCM, health is just *harmony* and disease discord. Because it is well known, *harmony* has to do with consonance of frequencies and can be achieved only through complex interaction of rhythms. So, a healthy physiologic state implies normal rhythmic behavior; physiologic malfunctions and diseases have to do with the disappearance of normal rhythms or emergence of abnormal rhythms. Diseases are *dynamic* in nature and can never be due to the minor changes of structure as may be exhibited by modern X-ray or imaging techniques, or the detection of minor increase or decrease of any biomarker molecules from biochemical examination. The review of clinical pathology in TCM will be covered later in Part 2.

The dynamic concepts to the *genesis of rhythms* in TCM as an application will now be applied. For example, the system of blood vessels in the human body is a closed vascular system containing a certain amount of blood. The vascular system is inherently connected with the heart and other internal visceral organs. Each point of the vascular system can be characterized by its elasticity and inertia as functions of time and frequency. Once the blood vessel is stretched due to blood flow from the heart and other visceral organs, the potential energy of its elastic wall can be generated. When the pumping force from the visceral organs stops, the potential energy of the vessel wall will be transferred to the kinetic energy of blood flow. Consequently, the synergy of visceral organs and blood vessels will guarantee a smooth blood flow due to the continuous conversion of potential and kinetic energies. The rhythmic motion of blood vessels will be pulsatile and can be palpated in many parts of the human body. The arterial pulse, for instance, contains information about the heart and other internal visceral organs. This is why the information about the heart and other visceral organs may be deduced from arterial pulse via the so-called pulsiconography of TCM as suggested by Manfred Porkert [42]. In summary, rhythms of the blood vessels

can be generated due to the kinetic/potential energy conversion, or *yin-yang* conversion, without invoking the pacemaker oscillations modeled by nonlinear differential equations. Different theories of the meridian system are reviewed next.

The essence of the meridian system

The question of whether the meridian system actually corresponds to any concrete anatomic structures is important in the study of acupuncture mechanism. The Standard International Acupuncture Nomenclature proposed by the WHO [1] claimed that there were 14 main meridians and eight extra meridians. However, the anatomic structure of these meridians remains baffling. Researchers have tried to provide evidence for the physical existence of these meridians since the early 1950s.

Nuclear tracers

Nuclear tracers were used to track the trajectory of acupuncture meridians in both humans and animals [43,44]. They were injected to a superficial depth of 3–5 mm. The tracers were supposed to migrate along the course of meridians but not nearby control samples. The migrations were not observed and interpretation of these results remained, however, controversial.

Conductance of skin surface and organizing centers

In addition, the electrical characteristics of meridians were intensively studied. Acupuncture meridians had been reported to have lower skin surface electrical resistance or higher conductance compared with adjacent control samples [45–47]. It was believed that higher skin conductance might be associated with higher density of gap junctions. A similar model indicating that acupuncture points were organizing centers in morphogenesis and the meridians were separatrices was proposed in [48]. According to this theory, for instance, the Governor meridian was a separatrix that divides the scalp into two symmetrical domains of different magnetic flux flow. Hence, the meridians might not have any anatomic structure in reality and the acupuncture points were just singular points or sinks at the surface magnetic field. It is fair to say that this theory might be important in growth control, cell migration, and morphogenesis, yet the meridian system in this theory had no connection with any concrete anatomic structure of human bodies *per se*. Even though this theory predicts high electrical conductance and high density of gap junctions at the acupoints and meridians, however, it would be difficult to use gap junctions and conductance to explain how the acupuncture might work in treating various physiologic malfunctions and diseases [48].

Abstract concept or invisible lines of medical acupuncture

There was also a Western medical acupuncture approach, based on the so-called present-day neurophysiologic principles [49]. The researchers of this group claimed that because no physical structure to explain these meridians had been found, the meridians were nothing but an abstract concept or the invisible lines on the surface of the body connecting acupuncture points. It is well known that the characterization of meridians is critical for the study of acupuncture mechanism and the success of clinical practice. If the meridian is nothing but an abstract concept or the invisible line on the surface of the body, then the Western medical acupuncturists have to use biochemical molecules or neurotransmitters to explain acupuncture mechanism instead. In Parts 2 and 3 of this review series, it will be pointed out that there is a huge gap between the approach of basic neuroscience and clinical neurology. Consequently, it is doubtful that patients can benefit from the treatments of these Western medical acupuncturists.

Dermatomes and Head zones

Joseph Needham once commented on books of acupuncture in Western language that can only be regarded as a second-best [50]. His comments are still valid and will be even more valid moving forward. It is, therefore, worth quoting verbatim his words as follows:

"In approaching acupuncture through the works of representatives of the present-day practitioners in the Western world some reserve should be exercised, for the following reasons: (a) very few of them have had reliable linguistic access to the voluminous Chinese sources of many different periods, (b) it is often not quite clear how far their training has given them direct continuity with the living Chinese clinical traditions, (c) the history in their works is liable to be minimal or unscholarly, (d) their accounts of theory are generally very inadequate, (e) they tend to adopt a too simplistic assimilation of classical Chinese disease entities to those of modern Western medicine, (f) the cardinal importance of sphygmology in Chinese differential diagnosis is almost ignored, and (g) their works are naturally so much influenced by modern Western concepts of disease etiology and semiography that they seem not to practice the classical Chinese methods of holistic classification and diagnosis."

Joseph Needham, however, had linguistic fluency in Chinese and had spent many years in the study of science and civilization in China. He indicated in his book [50] that the classic theory of *ching-lo system*, or the *meridian system*, was a complicated reticular network containing more than the 14 main meridians and eight extra meridians. According to Needham, the complete meridian system was not easily separable from the dermatomes, Head zones, muscles, sinews, tendons, blood vessels, lymphatics, and nerves. Even though his characterization of the meridian system is quite comprehensive, it is so broad that it covers almost every item in human anatomy and, hence, is not specific enough. His conjecture, however, about the dermatomes and Head zones being part of the meridian system was comparable to that of the nerve-reflex theory developed by Japanese scholars Fujita and Ishikawa et al in the 1950s [50]. They all believed

that acupuncture might work through the connection of dermatomes with the internal organs via the complex viscerocutaneous and cutaneovisceral relationships. However, this theory of meridians could hardly explain that puncture at different places of the same dermatome may have different actions on the internal organs.

Network of neurovascular bundles as fractal continuum

After studying voluminous traditional Chinese medical corpus, the meridian system was deciphered as the complex network of neurovascular bundles and their smaller branches, which connect internally with the viscera, and externally with the limbs and sensory organs [29–31,51]. It is not hard to support the foregoing interpretation with ancient textual evidence and modern histology. In the book of *Huang Ti Nei Ching* [52], for instance, it was said that the *blood* would go hand-in-hand with *qi* throughout the body via the network of meridians. The word *qi* in the context of the medical canon was meant to be the reticular system of nerve innervations and the word *blood* was certainly meant to be the fluid in the circulatory system. Hence, to equate the meridians with neurovascular bundles is conformable to the teachings of ancient sages. However, based on modern histology, every primary neurovascular bundle below the elbows and knees, for instance, contains an artery and motor nerves that are centrifugal and two satellite veins and sensory nerves that are centripetal. All of these units are enclosed in a connective sheath to form a neurovascular bundle. This is why the *primary meridians* that are located below the elbows and knees have been claimed to be the *neurovascular bundles* [29–31,51]. Hence, the *meridian system* in modern scientific language is equivalent to the notion of a complex *network* of neurovascular bundles and their smaller branches. This complex network is connected with internal viscera, peripheral limbs, and sensory organs. Anatomically, it is a continuum with self-similar fractal structure.

However, there are several major differences between the conception of neurovascular network in TCM and Western medical physiology. First, the neural system and circulatory system are almost always inseparable in the studies of acupuncture and TCM. When the functions of one system are impaired, then the functions of the other one are also influenced. In TCM, it would be stated as if *yang* or the nervous function is impaired, then the *yin* or circulatory function will be influenced. This is clearly a manifestation of the *yin-yang* concept in acupuncture and TCM. Notice that the *yin-yang* bifurcation of physiologic structures and functions can continue *ad infinitum*. For instance, the nervous system can be further divided into the central and peripheral, sensory and motor, sympathetic and parasympathetic pairs, etc. Similarly, the circulatory system can be divided into the heart and blood vessels, arteries and veins, etc.

Second, it is believed in TCM that the complex network of neurovascular bundles is connected internally with the viscera, and externally with the limbs and sensory organs. So, each organ of the human body is connected with one another through the neurovascular bundles and cannot be treated separately in clinical practice. In acupuncture, for instance, by adjusting the properties of neurovascular bundles in the right place at the right time, restoration of normal physiologic states is possible and feasible. In any case, the human bodies must be treated as a whole. This is the true meaning of the so-called *integrated* or *holistic* viewpoint of TCM.

Third, it is believed in TCM that the circulatory system forms a closed circuit and the nervous system is also a reticular network. The circulatory system is easier to understand for it is known that it consists of the heart, arteries, arterioles, venules, veins, capillaries, and blood. It can be considered a closed circuit because blood begins at the heart and finishes there through the combination of systemic and pulmonary circulations. It is the capillaries that can connect arterioles and venules and enable the exchange of water and many other nutrients between blood and surrounding tissues, etc. As to the reticular network of nervous system, it is not that clear. Notice that it is also much harder to detect its weak electromagnetic fields. However, this ancient reticular viewpoint of TCM is not totally baseless as can be seen from modern histology [53]. For instance, the endings of sensory nerve fibers that are distributed to the pacinian corpuscles, tactile corpuscles, and end-bulbs usually terminate after a convoluted course within these organs [53]. In addition, Boeke has also found out that the terminal motor nerves into the muscle cells ending within them in looplike expansions [53]. Hence, the distal ends of both the motor and sensory nerves form networks of loops and convolutions. As to the proximal ends of human cortex in the central nervous system, large size and numerous fibers of the myelinated nerve fiber network can be observed in the gray matter, in addition to the white matter, by using the Weigert-Pal staining method. This result indicates that the proximal end of the nervous system is also a reticular network of nerve fibers, as is the distal end. Therefore, the nervous system is indeed conformable with the TCM viewpoint of a circuit of reticular network. It is important to remark here that Cajal or Golgi staining methods can only show a few neurons, dendrites, and axons, but not the reticular network of nerve fibers. Also, the Nissl staining method can illustrate several layers of neural nuclei, but not the reticular network of nerve fibers either. It is only the Weigert-Pal staining method that can illustrate the reticular network of myelinated nerve fibers, i.e., part of the characteristic essence of meridians in TCM.

The next step is to characterize a meridian or its modern equivalent: a neurovascular bundle quantitatively for later applications in acupuncture mechanisms to be discussed in Parts 2 and 3. A neurovascular bundle has been characterized by its distributed conductance (G), resistance (R), inductance (L), and capacitance (C) as functions of time and frequency [29–31,51]. In Figs. 1 and 2, data supplied by two studies [54,55] were used to plot the longitudinal impedance diagram of the squid giant axon membrane and the input impedance diagram of the ascending aorta of a dog, respectively [51]. Notice that the longitudinal impedance of a nerve fiber is basically inductive at low frequencies and capacitive at high frequencies. The input impedance of an aorta is capacitive at low frequencies and inductive at high frequencies. Even though these two figures are

derived from a squid giant axon and the ascending aorta of a dog, it is logical to infer from these two impedance diagrams that the neurovascular bundles in humans can also be characterized by the transmission line impedance variables of *G, R, L*, and *C* possibly with different ranges of frequencies and magnitudes. It is noteworthy that the conduction signals in nerve fibers and blood flows in major blood vessels are pulsatile or alternating, so *L* and *C* are more important than *G* and *R*. In summary, in the network of neurovascular bundles, i.e., the modern conception of the system of meridians, the *inductive* and *capacitive* impedances of nerve fibers and blood vessels are the most basic and important characteristics; these two characteristics are complementary to each other in the sense that one is inductive and the other is capacitive at low and high frequencies. Recall that the neurovascular bundles contain an artery and motor nerves that are centrifugal and satellite veins and sensory nerves that are centripetal. Their electromagnetic effects are almost neutralized because these two flows are in opposite directions. Consequently, many physiologic conditions cannot be revealed by the anatomy of corpse for there is no more blood flow or nerve conduction. The old adage that "dead men tell no tales" holds true in TCM.

A schematic diagram to emphasize the mutual induction among the neurovascular bundles is shown in Fig. 3. Because it is only meant to explain the basic ideas, just two circuits, *AA* and *BB*, are shown. The nerve conduction signals and pulsatile blood flows in the contiguous circuits will interact with each other based on their respective self-impedances and mutual inductances. Consider first a vascular circuit *AA*, Fig. 3, with an alternating blood flow *I* flowing through it. In this case, the alternating or pulsatile blood flow will generate a very weak electromagnetic field. The magnetic circular flux through *A* is directly proportional to *I*, and the total flux that interlinks with a nearby neural or vascular circuit *B* is also proportional to *I*. This means that the contiguous circuits in neurovascular bundles will be mutually influenced. When the blood flow is started, stopped, or varied in circuit *AA*, it will induce a corresponding change within circuit *BB*. In neurovascular circuits, the mutual inductance and capacitance are often used to transfer energy or information from one circuit to another. The impedance can be defined as the ratio of voltage to current.

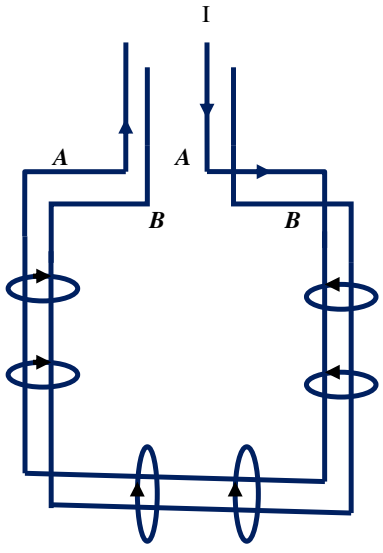

Fig. 3. Schematic diagram of mutual inductance in neurovascular bundles AA and BB.

A myelinated neural circuit *AA* can be considered next, using the same Fig. 3, with a solenoidal current flowing within the myelin sheath. In this case, the current flow will generate a very weak magnetic field within the axons. The magnetic flux will induce a basic "nerve tone" which, just like the "muscle tone" for the muscles, can align the neurofibrils in a ready state that is capable of transmitting either the afferent sensory information to the brain or efferent motor signals to the peripherals. The situation is very much like a solenoid is wound through a tube filled with iron filings. The iron filings will align themselves in a conformable way with the magnetic field caused by a variable current in the solenoid. By examining the shapes of iron filings, the original magnetic field or the variable current can conversely be deduced in the solenoid. Similarly, the shapes of neurofibrils in the axon can convey the information from either afferent sensory or efferent motor signals. In addition, whenever the nervous signals are started, stopped, or varied in circuit *AA*, the mutual inductance will also induce corresponding changes in circuit *BB*. It will be illustrated in Part 3 of this series of articles that this proposed model of nerve conduction, with myelin and neurofibrils as key components, is much closer to neurophysiologic reality in vivo and neurology in clinical practice as compared with that of Hodgkin and Huxley [56].

In Fig. 4, a feasible model of the meridian system based on the previous notions has been proposed [29–31]. In this figure, the primary meridians are characterized by transmission line impedance $Z_2,\ldots,Z_{3n-1}$ for $n = 1, 2, \ldots, N$. Here N stands for the number of primary meridians in TCM. According to TCM, in addition to the primary meridians, i.e., neurovascular bundles, there are other smaller branches that connect to form a reticular network system. For simplicity, only one of the smaller branches will be drawn in red vertical bars here. The rationale for using cable theory in modeling meridians is actually derived from organogenesis and histology. It is well known in organogenesis that different systems of the entire organism develop simultaneously [57]. They also interact and modify each other through the network of neurovascular bundles. In TCM, the meridians have the capability to control and regulate visceral organs. In Fig. 4, the visceral organs that are closely related to their respective meridians are characterized by load impedances $Z_3,\ldots,Z_{3n}$, for $n = 1, 2, \ldots, N$. Finally, $Z_1,\ldots,Z_{3n-2}$, for $n = 1, 2, \ldots, N$ are used to represent proper impedance matching so that each visceral organ and its associated neurovascular bundles will derive a proper ratio of energy or information flow from either the internal or external generator of rhythms with generator impedance Z_g. So as not to complicate this figure, the bifurcations of complex neurovascular networks will not be drawn further. It is understood, however, that the neurovascular network will have a self-similar structure as in any fractal continuum. In Parts 2 and 3 of this series of articles, this network will be used to explain how acupuncture works in analgesia and therapeutics.

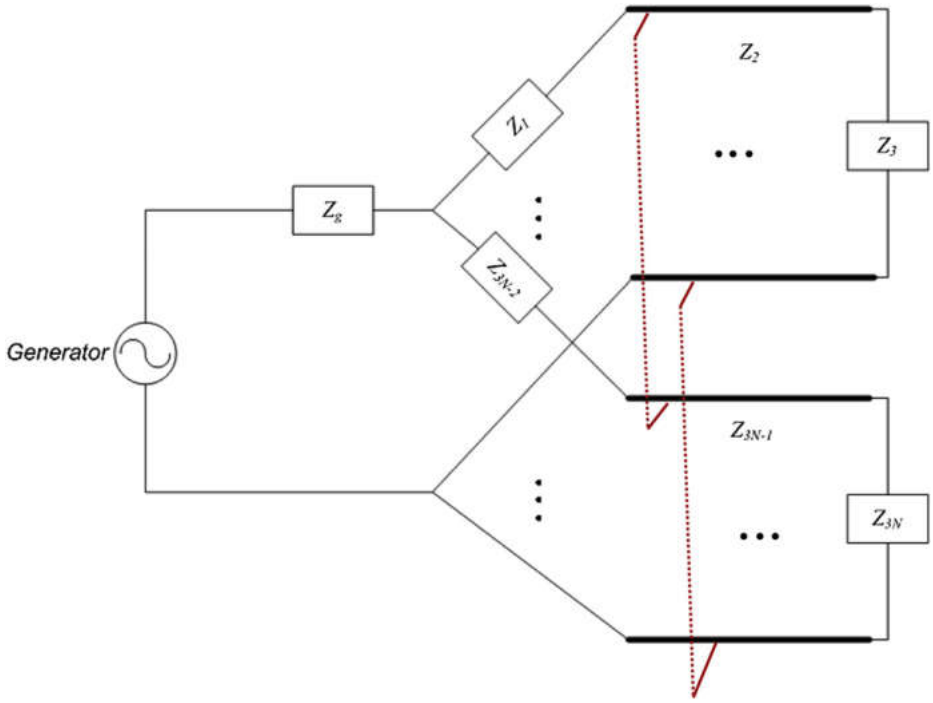

Fig. 4. A tentative model of the meridian system in acupuncture. From "Physiological rhythms, dynamical disease, and acupuncture," by S. Chang, 2010, Chin J Physiol,53, p. 72−90. Reprinted with permission.

Conclusion

In this article, various studies have been reviewed in an attempt to answer one important question: what is the essence of meridians? A number of schools of thought do not admit the existence of meridian system at all. Some of the prevailing models, however, have defied simple interpretations or lacked the capability of explaining the mechanisms of curing various diseases. To characterize and model the meridian system in line with ancient Chinese medical canons, (1) the chaotic wave theory of fractal continuum to mathematize the basic concepts of Chinese natural philosophy has been proposed; (2) this theory has been applied to characterize the meridian system in acupuncture; and (3) a reticular network model based on transmission line and cable theory has been adopted. The meridian system has been designated as the complex network of neurovascular bundles and their smaller branches of fractal continuum. The key properties of this network can be characterized by its distributed electromagnetic dynamic variables of *G, R*, *L*, and *C*. It is hoped that, based on a better understanding of the meridian system in Part 1, mechanisms of acupuncture analgesia and therapies can be revealed in Parts 2 and 3 of this series of articles.

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