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RESEARCH ARTICLE

A Discovery of Low Hydraulic Resistance Channel Along Meridians

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Abstract
A hydro-mechanic model was put forward to study the fundamental nature of acupuncture meridians. The basic state of low hydraulic resistance was tested on humans and mini pigs using three methods. The first, a modified Guyton's method, proved that there was lower hydraulic resistance on meridians compared with non-meridians. The second scanning method involved a single pressure transducer that can find the lowest resistance point in tissue, and the third method used two transducers and provided a more stable measurement. Using the latter method, low hydraulic resistance points were found very close to low impedance points along meridians. The transmission of artificial interstitial fluid pressure waves was measured to examine their connection to the low resistance points, with the result that a good connection between the points was confirmed. This means the points form channels along the meridians that we refer to as low hydraulic resistance channels. The channel was imaged through isotopic tracing and a migration of isotope ^{99m}Te could be found along the channel. The layer of the channel was detected by injecting Alcian blue and the track was found beneath the skin. All of the above experiments suggest the existence of a new type of channel in living tissues that has not yet been described in modern science, but coincides quite well with the Qi channel theory of traditional Chinese medicine.

1. Introduction

Meridians are special lines distributed longitudinally on the human body which are similar to the meridians on the earth. There are channels under the lines through which Qi and blood flow according to the theory of traditional Chinese Medicine (TCM). The meridians also connect and play a role in regulating the viscera. There are more than three hundred special points along the meridians where acupuncture is given whenever a person has a disease. Consequently, the meridians are also called acupuncture meridians or medical meridians in some contexts. Acupuncture was introduced to the western world many years ago and has been accepted as an alternative medicine by many countries, demonstrating good curative effects for many chronic diseases, as well as fewer side effects than some biomedical treatments. How do we explain the effect of acupuncture from the point of view of modern medical knowledge? Although a large number of studies on acupuncture

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have been conducted over the last forty years in China, as well as other countries such as Japan, Korea, America and Germany, no great progress has been made in explaining the mechanism of action of acupuncture. In the classic theory of TCM, on the other hand, the function of acupuncture is explained as simply to dredge the channels in order to make Qi and blood flow better. Ancient people had no need to further “explain” acupuncture because they believed in the existence of meridians and Qi and knew what they were. But meridians and Qi have become a mystery to modern people. It is unwise to try to explain the principles of acupuncture without thorough consideration of meridians and Qi.

Some scientists have really made efforts to look for the channels under the meridians, trying to find special biologic structures. One famous character is Kim Bonghan from North Korea. In 1963, he claimed to have found a tubal structure which was called a Bonghan duct [1]. Later on, Chinese researchers tried to repeat the results but failed and such research was set aside for many years. It was not until 2000, that Kwang-sup Soh, a professor at Seoul University, began to study Kim’s findings using new morphologic techniques and found novel threadlike structures in blood vessels, lymph vessels and on the surface of internal organs. However, he was not able to positively identify such structures on peripheral tissue along meridian pathways [2].

In the 1960s, a Japanese scientist named Fujita put forward a kino-dynamic hypothesis about the meridians, which presumed that the meridians are flowing pathways of extravascular fluid which depend upon the dynamic force of muscle contraction and have a structural basis of loose connective tissue [3]. As loose connective tissue is distributed in many places in our body, particularly in subcutaneous layers, it is hard to distinguish a special pathway just under the meridian lines. Also, as a general principle, we should consider that the flow of extravascular fluid can not be ascribed to the meridians without a solid boundary. During roughly the same era, another famous Japanese researcher, Nakatani, found low impedance points along meridian lines, which he called Ryodoraku. In China, meridian research formally began in the 1970s when a phenomenon of propagated sensation along channels (PSC) was found. PSC was then observed in large-scale studies and some rules about this phenomenon were discovered. For example, it moves at a slow speed, can be stopped by mechanic pressing, is bidirectional, and can move toward or away from a diseased area of the body. The phenomenon proved the functional existence of meridians but lacked morphologic evidence. Later on, further studies were carried out to find physical characteristics and related structures. One important study concerned the migration of isotope along channels (MIC). This was first discovered by Vernejoul in France [4] and then studied by Meng and his group in China [5]. In these experiments, slow movement of ^{99m}Te along meridians was observed after injecting the isotope into an acupoint, while only a local spread and a blurry movement toward the meridian nearby was found when injecting the isotope outside acupoints. Acupuncture can accelerate the migration along meridians. Unlike PSC, MIC is a relatively simply physical phenomenon which follows physical laws. It is possible to reveal the fundamental nature of the channels by studying the cause of MIC.

2. A Hydro-mechanic Model of the Channels and Qi

2.1. Darcy’s law

As there was no evidence suggesting that the migration of ^{99m}Te was in blood or lymph vessels, it was proposed that the media of the migration might be the interstitial fluid, namely extravascular fluid, a view that was close to Fujita’s. The key problem is determining how the fluid drives isotopes along a certain route without a solid boundary. The interstitial fluid flow is permeable in porous media with a low Reynolds number. Darcy described the flow in 1856 as Darcy’s law:

$$Q = KA\frac{\Delta P}{L} \qquad (1)$$

Q is flow rate. K is hydraulic conductivity which relates to the flowing liquid.

$K=k/\mu$, k is special hydraulic conductivity determined only by the property of tissue and μ is the dynamic viscosity coefficient of the liquid. A and L are the area and length of the tissue. ΔP is pressure gradient.

Usually it is difficult to determine the A, L and μ while Q and ΔP are possible to measure.

$G=Q/\Delta P$ is called conductance and $R=\Delta P/Q$ is called resistance in Guyton’s paper [6] while R is called hydraulic resistance (Rh) in Livick’s paper [7]

Darcy’s law can be also represented as the average speed of liquid

$$V = -\frac{k}{\mu}\nabla P \qquad (2)$$

From Darcy’s law, when k is higher, Rh is lower. k represents the permeability of tissue which is positively related to the number of pores and the connectivity in tissue.

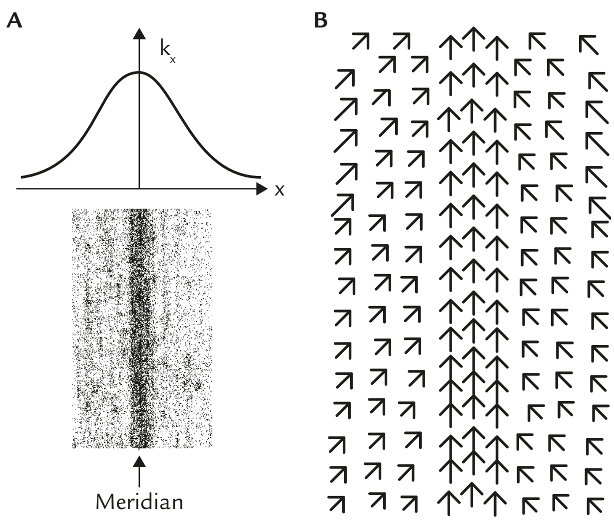

Figure 1 (A) The porous distribution around a meridian. (B) Flow pattern of interstitial fluid towards and along meridians.

2.2. Hypothesis of the meridians and Wei Qi

Assuming there are many pores and good connections between the pores in the tissue of a meridian, then k specifically will gradually increase toward the meridian (Figure 1A). According to the question (1) and (2), there will be a higher flow rate or a higher average flow velocity and the interstitial fluid will flow toward and along the meridian following paths of lower hydraulic resistance (Figure 1B). The hypothesis is called “low hydraulic resistance hypothesis for acupuncture meridians”. According to the theory of TCM, Wei Qi flows outside the *mai* or blood vessels, therefore we hypothesize that the flow of interstitial fluid is actually what the ancients described as Wei Qi.

2.3. The boundary-like effect of meridians by Fick’s diffusion law

In the classical theory of TCM, there are channels under the meridians in which Qi is bound and flows. Such characteristics can be understood by Fick’s diffusion law.

$$N_i - X_i \Sigma N_j = - D_i C \nabla X_i \quad (3)$$

Here N_i is the flow rate of solute and ΣN_j is the flow rate of solvent, which is interstitial fluid here. X_i and ∇X_i are the concentration and concentration gradient of solute. D_i is the diffusion coefficient of solute. As there is a flow toward the meridian, the diffusion of the solute from the meridian ($D_i C \nabla X_i$) will be balanced by the flow of solvent to the meridian ($X_i \Sigma N_j$). Therefore, the solute can be restricted approximately along meridian lines and can serve as a channel despite the lack of a solid, physical boundary.

3. Experimental Verification of the Hydro-mechanic Model

3.1. Measurement of hydraulic resistance (Rh)

3.1.1. Modified Guyton’s method

Levick measured Rh using a hanging bottle to inject saline into tissue and counted the drop rate in the middle of the stream [7]. The problem with this measurement is that if the needle stays in the tissue too long, the accumulated liquid will increase the pressure in the tissue and reduce the flow. Guyton measured the hydraulic conductance using two chambers with a plastic member in the middle that can produce a pressure differential between the two measuring needles [6], thereby causing a circulating flow. This method overcame the accumulation problem. A modified Guyton’s technique was used by the author in meridian research. The device used is shown in Figure 2.

The experiment was done on 15 rats and 4 mini pigs. The meridians were determined by using an instrument to measure impedance (57-6F30, made in China). Conductance was measured on the meridian and outside the meridian in sub cutis. The results in rats showed 14.5×10^{-8} (SD=15.92, n=75, unit: cm^4/dyn-sec) on meridians, which was very significantly higher than the conductance of 9.55×10^{-8} (SD=14.01, n=71) outside the meridians ($p<0.005$). The conductance in mini pigs was 1.72×10^{-5} (SD=2.19, n=59) on meridians, which was also very significantly higher than the conductance of 0.78×10^{-5} (SD=3.17, n=71) outside the meridians ($p<0.005$) [8]. These results indicate a low Rh along meridians.

3.1.2. Scanning method with single pressure transducer

Although the results showed an average lower Rh along meridians, the place of lowest resistance cannot be ascertained using the above method. To find the lowest resistance, the measuring needle must move in tissue and monitor the Rh continuously. A device that scans and measures Rh was invented for just this purpose (Figure 3).

The experiment was conducted on six anaesthetized mini pigs weighing 10–12 kg, which were obtained from the animal center of Beijing Agriculture University. The needles used were no. 9 (internal diameter 0.9 mm) injecting-type needles with a side

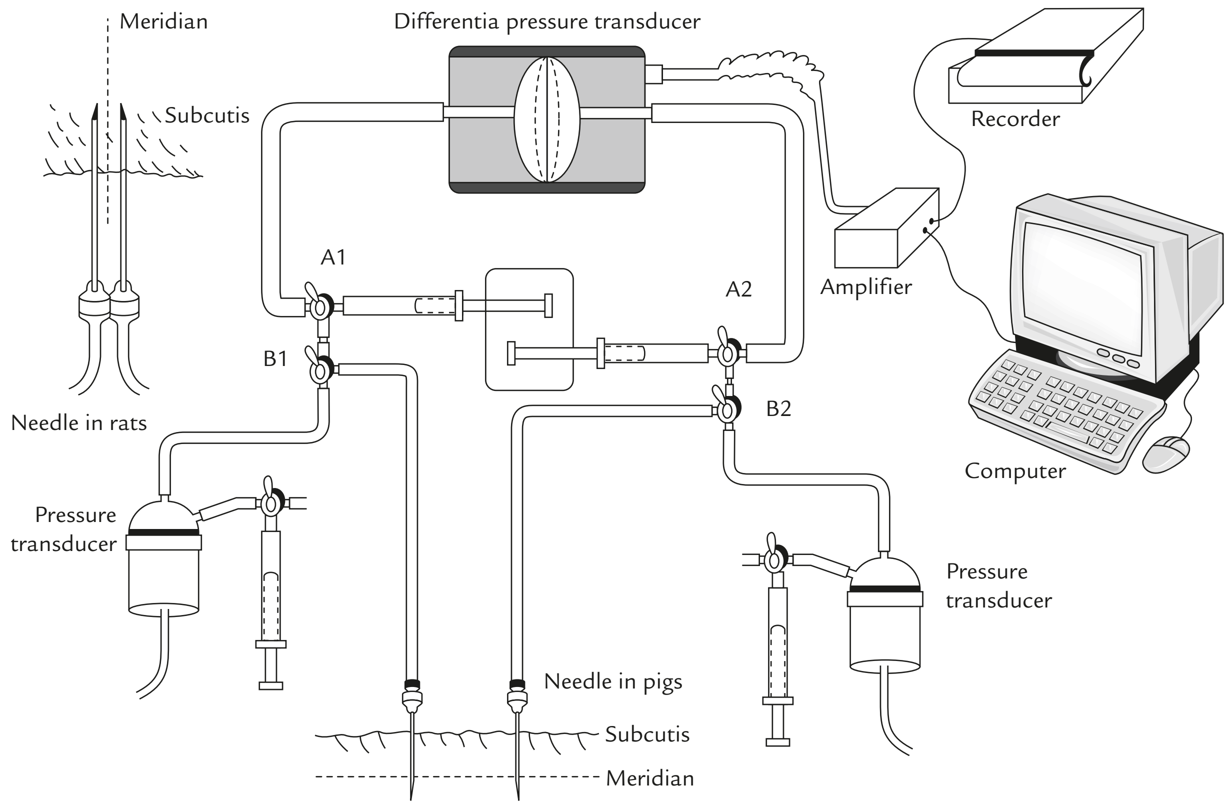

Figure 2 A modified Guyton's method of measuring hydraulic conductance.

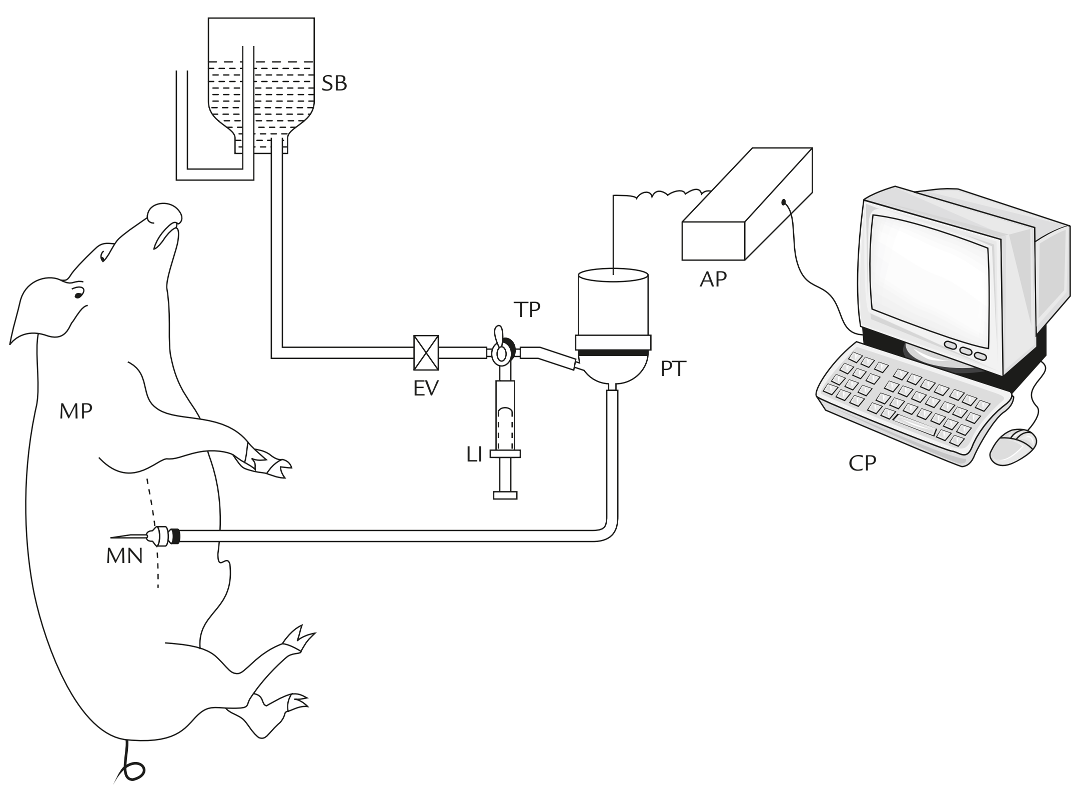

Figure 3 A scanning device to measure hydraulic resistance. AP=amplifier; CP=computer; EV=electric magnetic valve; MN=measuring needle; MP=mini pigs; PT=pressure transducer; SB=saline bottle; TP=triple valve.

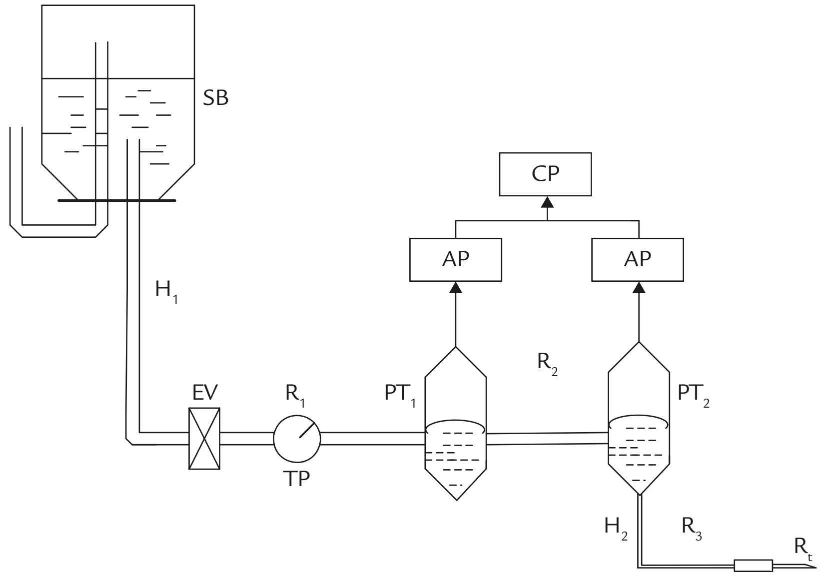

Figure 4 The measuring system of hydraulic resistance with double-pressure transducer. AP=amplifier; CP=computer; EV=electric magnetic valve; PT=pressure transducer; SB=saline bottle; TP=triple valve.

hole of 1–2 mm long. Twenty to thirty fine Nylon fibers were put inside the needle. The opening at the tip was blocked to prevent blockage from occurring during its movement in tissue and so that water could only flow from the side hole. The same needles were used to measure the interstitial fluid pressure (IFP) in Fadnes' work, he, however, referred to this as the wick in needle (WIN) method [9]. The approximate value of the resistance in tissue outside the side hole of the needle (MIN) was positively correlated with the pressure in the pressure transducer (PT). The needle was inserted into the subcutaneous tissue and moved horizontally across the meridian line forward and backward. Utilizing this device and method, a lowest hydraulic resistance point (LHRP) could be found, which in most cases was narrow and near the low impedance points (LIP) along meridian lines. Of 234 unique meridian locations tested, 222 LHRP could be found. The presenting rate was 95%. Each location was measured throughout an area comprising 2.6 cm. In almost all cases, only one LHRP was found, with only six locations having two LHRPs. The average resistance on the LHRP was $1.69 \pm 1.94 \times 10^7$ dyn·s·cm^{-5} while the average resistance in areas outside LHRP was 31.46 ± 104.35 dyn·s·cm^{-5} and was greatly significantly higher than LHRP based upon the Wilcoxon rank sum test ($p<0.001$) [10].

3.1.3. Scanning method with two pressure transducers

The greatest advantage of this particular scanning method was that it could measure the resistance continuously; however, one drawback was that it could be influenced by the respiration of the animal, particularly the mini pigs. Consequently, the pressure curve, which reflected Rh, was not very smooth. To overcome the disturbance from the vertical movement of the needle, a double-pressure transducer system was designed to improve the accuracy of the measurement (Figure 4).

The resistance (R_t) in tissue was positively related to the pressure difference between the two transducers

$$\Delta P = \frac{R_2}{R + R_t} H_1 \qquad (R = R_1 + R_2 + R_3)$$

R is the whole resistance from the bottle to the needle, and is much lower than the resistance in tissue and can therefore be ignored. R_t relates to ΔP in an inverse and almost perfectly linear manner; this can be shown on the screen of a computer. As the fluctuation of the needle influences both transducers simultaneously, the difference between the transducers will not change. Once implemented, the curve became very smooth and the LHRP could be seen more clearly (Figure 5).

This experiment was carried out on mini pigs and humans. In 12 healthy volunteers (5 male, 7 female, average age 34.5 years), 36 sites were measured across the gallbladder meridian on the lower limb. LHRP were found when the needle moved forward or backward. Unlike mini pigs, usually two LHRP were found during each measurement, with one LHRP distributed along the gallbladder meridian, while the other formed another line deviating from the gallbladder meridian by 1–2 cm. The latter also had low impedance and

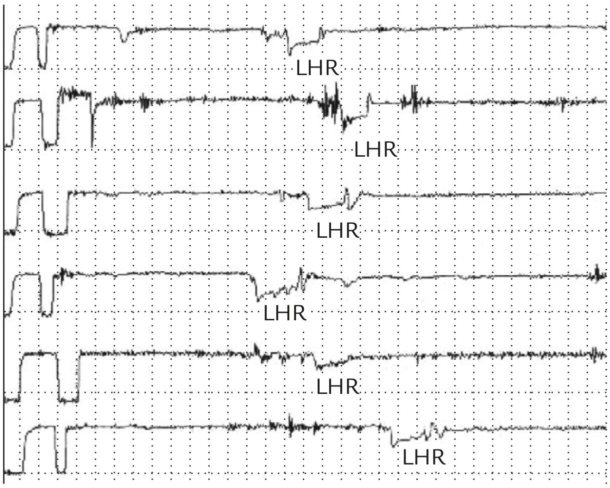

Figure 5 The hydraulic resistance curves on the stomach meridian of pig no. 8. The LHR marked the low hydraulic resistance places on the curves.

was thought to be a branch of the gallbladder meridian. In rare cases, three LHRP were found. The results are shown in the Table.

Table Hydraulic resistance on human (mean$\pm$standard deviation$\times 10^7$ dyn$\cdot$s$\cdot$cm^{-5})

	n	LHR points	Control area
Forward	62	3.41±2.89*	40.50±38.13
Backward	11	1.34±0.61*	8.24±7.84
Whole	73	3.10±2.77*	35.64±37.08

*$p<0.001$, compared with control area. LHR = low hydraulic resistance.

3.2. The coincidence with low impedance points

Low impedance points (LIP) have been found on human meridians by many researchers. Using a pulse impedance detector, 57-6F30, Zhu found LIP along meridians that were less than 1 mm in width on healthy volunteers [11]. The LIP was then used to determine the exact position of meridians in many studies. The sites of LHRP usually overlapped the LIP or were very close to LIP in mini pigs. The mean distance between LHRP and LIP was 1.4±1.2 mm on the kidney meridian, 1.6±1.7 mm on the stomach meridian and 1.7±1.4 mm on the conceptual vessel meridian. The total mean distance was 1.5±1.4 mm, which amounted to a near overlap between LHRP and LIP by contrast with a 30–40 cm average girth on the trunk of mini pigs. The LHRP distributed linearly along the classic meridians.

3.3. The transmission of IFP wave

The linear distribution of LHRP is not, in and of itself, adequate evidence to confirm that they form continuous related channels. A new method was therefore invented to determine the possible connections between the LHRPs.

After finding a LHRP, the needle was left in place and 0.2 mL saline was rapidly infused into the tissue. A mechanical press of 150–200 g was given immediately after the injection. An artificial interstitial fluid pressure wave (AIFPW) was produced and transmitted in the tissue. At another site located 5–10 cm from the first LHRP, two pressure transducers were used to measure the AIFPW on LHRP and a control point 0.5–1 cm beside the LHRP simultaneously. The mechanical press was given twice at one site and the pressure in another LHRP and the control point were both measured and sent to a computer.

Thirty nine pairs of points were measured. The mean amplitudes of AIFPW were 3.4±2.4 mmHg and 2.3±3.2 mmHg in LHRP and non-LHRP (control point), respectively, which was significantly different ($p<0.05$). This suggests that the interstitial fluid pressure wave can be transmitted between the LHRPs.

The results showed a strong connection between the LHRPs along meridians and suggests that a continuous channel exists in the tissue under meridians. If this hypothesis is true, the LHRPs are intersecting points, which are observable when the needle is moved across a channel. We refer to the channel as a low hydraulic resistance channel (LHRC) or low hydraulic resistance channel along meridians (LHRCM).

3.4. Presentation of the channel by isotopic migration

When measuring resistance and the transmission of pressure, a LHRCM could be detected in subcutaneous tissue, but is hidden in tissue that cannot be seen directly with the naked eye. To observe the channel directly, an isotope tracing method was used.

The isotope was fresh $^{99m}TcO_4^-$ saline (5–10 mCi/mL) which has a half-life of 6 hours. A γ camera (Type GCA-501Sr, Japan) was used to observe the track of the isotope. The experiment was carried out on the stomach meridian in mini pigs. Two LHRPs, 30 cm apart from each other on the stomach meridian, were measured and marked with very small amounts of isotope before the observation. Another LHRP, located in the center between the two LHRP on the stomach meridian was also selected and injected with the isotope. After injecting 0.1 mL $^{99m}TcO_4^-$ into the tissue, the migration of the isotope was observed

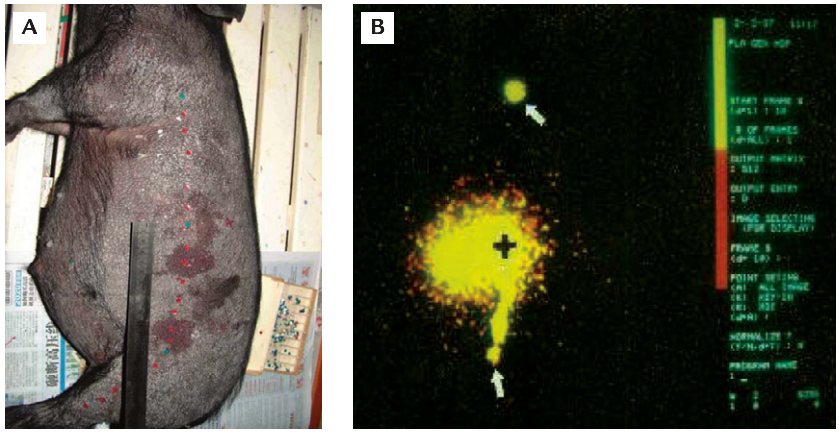

Figure 6 (A) The sites of isotope injection and marked points (green points). (B) The migration of isotope along the channel. +=injecting point; ↑=two marked low hydraulic resistance points.

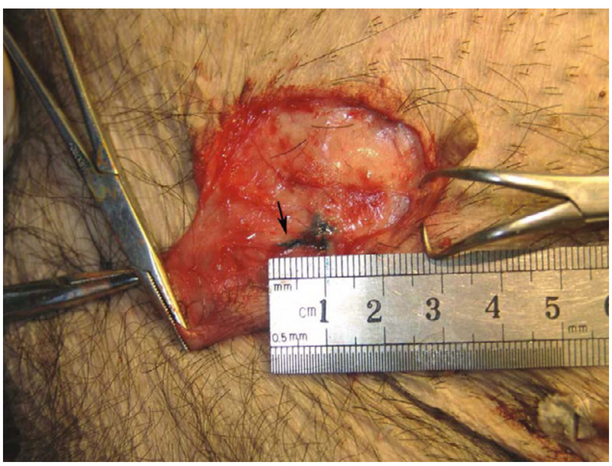

Figure 7 A demonstration of LHRC (black arrow) using Alcian blue dye.

using the camera (5 sec/1 frame). In total, 32 frames were taken over a period of 160 seconds.

The experiments were carried out on the stomach meridian in six mini pigs. It was shown in two cases that, after the injection, a migration of isotope could be found along the meridian toward the other LHRP (Figure 6). The migrating track was 14 cm in length and moved in a distal direction. The latent period (the interval between completing the infusion and the appearance of the track) was less than 5 seconds and the approximate speed of the migration was 4 mm/s.

3.5. Morphologic location of LHRP

Two LHRPs on the kidney meridian corresponding to K14 and K15 on the human body were located in mini pigs. After the connection between the two points was determined using a pressure transmission method, 1 mL of Alcian blue was prepared following Lee's method [12] and was gradually injected into one point over the course of 3 hours. The skin was then incised and removed around the injected point and the subcutaneous tissue was exposed. Photos were taken with an 828 Sony digital camera.

A track of 10 mm of Alcian blue dye was found along the LHRC in subcutaneous tissue while no dye was observed on the skin around the LHRC. The width of the track was about 1 mm (Figure 7). The micro structure of the track will be studied in the future.

4. Discussion

In TCM theory, Wei Qi flows outside vessels (*mai*) and circulates in a regular pattern with Ying-Blood, which circulates within blood vessels warming muscles, expanding the interstices (*cou li*) which correspond to pores and controlling sweat glands. The description of Wei Qi in classic TCM theory is quite similar to what we know about interstitial fluid in modern physiology. Interstitial fluid is an important body fluid, which connects blood vessels, lymph vessels and cells. But modern physiology pays little attention to interstitial fluid. There is even debate about whether there is actual free flow of interstitial fluid. Some scientists like Guyton in America thought that there is no freely moving interstitial fluid in tissue because it is all combined with other molecules and therefore exists in a gel-like state. He based this upon the results obtained from measuring negative interstitial fluid pressure [7]. Other scientists such as Aukland in Norway and Levick in England however thought that there were two phases in the interstitium, one is a gel phase and the other is a free fluid phase. The free fluid can flow between blood and lymph vessels and plays an important role in regulating extracellular contents [13,14].

If the free fluid exists in interstitium, its flow will follow Darcy's law and if the interstitial hydraulic resistance is heterogeneous, a directional flow will appear. In terms of ancient TCM theory, we can say that descriptions of Wei Qi flow as occurring "half in skin and half along meridians" are suggestive. Classical descriptions of Wei Qi functioning like underground water also bring Darcy's law to mind.

Fujita's hypothesis of an extravascular fluid pathway for meridians turned out to be correct; however he failed to explain how they could function as channels. Our hydro-mechanic model indicated a basic condition of low hydraulic resistance, which explains the flow of fluid. This can be tested experimentally and, when Fick's diffusion law is applied, can explain how they form channels without corporeal boundaries.

The method of measuring hydraulic resistance we used in human subjects retained all the advantages of techniques used in other experiments. It proved to be an ideal technique to ascertain the exact location of the channels, and will, no doubt, be very important in future research.

The mini pig was used because its skin structure, including the subcutis, is quite similar to humans and its body is relatively large making it is easy to measure the meridians and search for LHRC. Our experiments suggest that the technique of measuring the resistance is suitable for pigs and humans, but difficult to use on smaller animals like rats and rabbits. So the usage of pig was another important factor in finding LHRC. The pigs were bred especially for experiments by Beijing Agriculture University.

Our results showed there was lower hydraulic resistance along meridians and the existence of a continuous low hydraulic resistance channel close to the meridian. The discovery of LHRCs provides a physiologic explanation of the medical meridians for the first time. The condition of low hydraulic resistance causes more fluid to flow along meridian lines compared with non-meridian areas, according to Darcy's law. In some cases, such flow could be seen by the movement of isotope tracks. The isotope tracing method had been used on humans in other studies to show that isotopes migrate along meridian lines. Our studies with pigs, we believe, provide an explanation of the phenomena. Our studies show that the migration of isotope in the human body represents the interstitial fluid flow along LHRCs.

Because the isotopic experiment on mini pigs was done in a different place far from our lab, transporting the pigs might have caused the deviation from the LHRP shown by the measuring needle, which, in turn, influenced the isotope migration and made the propagation less obvious. The results of the morphologic studies confirmed that the channels mainly existed in subcutaneous tissue. This method has already been used to study acupuncture points and meridians by Ifrim-Chen and Lee [12,15]. As Alcian blue can stain mucopolysaccharides such as hyaluronic acid, the track should be in the interstitium, not in blood or lymph vessels. Considering that hyaluronic acid usually doesn't move with interstitial fluid, it is not surprising that the track of Alcian blue is not very long. In our previous study, a fluid channel in gel was made artificially and some physical features like low electric impedance, low hydraulic resistance and high acoustic transmission, which were found on human meridians, could be reproduced in the model [16]. The physiologic significance of LHRC has been discussed previously in the lead author's book [17]. The facts support the hypothesis that the interstitial fluid channels form the physiologic and morphologic basis of the acupuncture meridians described in detail by the ancient Chinese more than two thousand years ago.

Acknowledgments

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