Advances in microcirculation monitoring and physical factor therapy techniques in diabetic foot

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Abstract: Diabetic foot is one of the most severe complications of diabetes. It is caused by high blood sugar, resulting in combined neuropathy and various degrees of peripheral vascular disease, leading to local microcirculation disorders. This condition can trigger infections, ulcers, and deep tissue damage in the lower limbs. In severe cases, gangrene may occur, leading to amputation. Therefore, timely microcirculation monitoring of the feet in diabetic patients can help detect early blood supply issues. Prompt and effective intervention and treatment for diabetic patients with microcirculation disorders in the feet can prevent the occurrence and development of diabetic foot. Physical factor therapy utilizes various forms of physical energy to induce reactions in the body, such as dilating blood vessels, increasing blood flow, and promoting tissue blood supply. Simultaneously, it stimulates nerves and muscles, aiding in improving nerve conduction and promoting nerve regeneration. This helps prevent and improve microcirculation disorders in diabetic feet. This article outlines the microcirculation disorders in diabetic feet, along with monitoring and treatment methods. It focuses on the principles and efficacy of common physical factor methods for microcirculation intervention, as well as research advancements in their clinical application for diabetic foot. This information serves as a reference for the treatment and adjunctive research of diabetic foot.

1. Introduction

Diabetes is a chronic metabolic disease characterized by persistent elevation of blood sugar levels. Prolonged high blood sugar can cause serious damage to the heart, blood vessels, eyes, kidneys, and nervous system. According to a study published in The Lancet, as of 2021, there are approximately 529 million diabetes patients globally, making diabetes a global public health issue. China has the highest number of patients, reaching 140 million, and it is estimated that this number will increase to 164 million by 2030[1]. Diabetic foot, as one of the common chronic complications in diabetes patients, involves neuropathy and peripheral vascular lesions in the lower extremities, leading to ulcers and necrosis in the feet, with an incidence rate as high as 15%-25%[2]. Studies have shown that the amputation rate caused by diabetic foot is 19%-27%, and the mortality rate is higher than that of breast cancer, prostate cancer, and others[3]. With the aging population and the increasing prevalence of diabetes, the incidence of diabetic foot continues to rise. The amputation and mortality rates in diabetic foot infection patients are higher than in non-diabetic foot infection patients, mainly due to peripheral neuropathy, which leads to reduced or lost sensation in the feet, delaying the timing of treatment. Additionally, high blood sugar can cause vascular lesions, affecting blood supply to the feet and leading to microcirculation disorders[4]. Microcirculation disorders are one of the main causes of diabetic foot, and understanding these disorders can assist doctors in detecting circulatory issues in the feet at an early stage. This knowledge enables them to implement effective interventions, preventing diabetic patients from developing foot complications such as ulcers and gangrene. Additionally, microcirculation is crucial for wound healing, and diabetic patients often experience slow wound healing and increased susceptibility to infections due to microcirculatory impairments. By gaining insights into microcirculation conditions, doctors can employ targeted treatment approaches to promote wound healing and reduce the risk of infections. Therefore, early monitoring of microcirculation in diabetic patients’ feet and active management of diabetic foot ulcer wounds to promote wound healing are of paramount importance. Improving tissue microcirculation, accelerating capillary growth, and enhancing blood supply levels through physical interventions play a crucial role in ameliorating microcirculation disorders in the feet, facilitating foot ulcer healing, preventing infections, and reducing the risk of amputation[5]. This article provides an overview of the research progress, clinical applications, and treatment of diabetic foot and its microcirculation disorders.

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2. Diabetic foot and microcirculation disorders

Diabetic foot is one of the common and severe complications in diabetes patients, primarily associated with three aspects: neuropathy, vascular changes, and compromised immune system function[6]. Diabetes-induced neuropathy results in diminished sensation in the feet, leading to a reduced ability to perceive injuries and pain. This makes minor traumas less noticeable, thereby increasing the risk of infection and ulcers. Vascular changes caused by elevated blood sugar levels impact blood supply to the feet, resulting in tissue ischemia and delayed ulcer healing. Vascular alterations also accelerate the spread of infections in the patient's feet. Additionally, under conditions of elevated blood sugar, the immune system function in diabetic patients is suppressed, making them more susceptible to infections, further exacerbating foot complications. The grading of diabetic foot is shown in Table 1.

Table 1. The grading of diabetic foot

<table>
<thead>
<tr>
<th>Grade</th>
<th>Clinical Presentation</th>
</tr>
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<tbody>
<tr>
<td>Grade0</td>
<td>Feet with risk factors for diabetic foot ulcers, currently without ulcers.</td>
</tr>
<tr>
<td>Grade1</td>
<td>Ulceration on the surface, clinically no infection.</td>
</tr>
<tr>
<td>Grade2</td>
<td>Severe ulceration occurs, often with intersecting cellulitis or bone infection.</td>
</tr>
<tr>
<td>Grade3</td>
<td>Deep infection with concurrent bone involvement or abscess.</td>
</tr>
<tr>
<td>Grade4</td>
<td>Localized necrosis.</td>
</tr>
<tr>
<td>Grade5</td>
<td>Gangrene involving the entire foot.</td>
</tr>
</tbody>
</table>

Microcirculation disorders are a significant factor contributing to diabetic foot, directly impacting the blood supply and nutrition of foot tissues, thereby increasing the risk of infection and ulcers. As shown in Figure 1. The relationship between microcirculation disorders and diabetic foot is reflected in alterations in hemorheology, endothelial dysfunction, inflammation and oxidative stress, as well as ischemia and hypoxia[7]. Diabetes patients often exhibit high blood viscosity and a procoagulant state, leading to impaired microcirculation. The elevated viscosity hinders smooth blood flow in small vessels, affecting blood supply to foot tissues and predisposing to diabetic foot. Moreover, microcirculation disorders result in ischemia and hypoxia in foot tissues, exacerbating the formation of diabetic foot ulcers due to a lack of essential oxygen and nutrients. The relationship between diabetic foot and microcirculation disorders is intricate and closely interconnected. Effective management strategies aim to monitor microcirculation blood flow in the feet, improve blood sugar control, and intervene promptly, thereby slowing the progression of diabetic foot and enhancing the quality of life for patients.

3. Microcirculation monitoring technology and applications

Microcirculation monitoring is a crucial method for assessing blood supply and tissue perfusion in the feet. It aids in the early detection of microcirculation abnormalities, enabling the implementation of effective intervention measures to slow down or prevent the onset and progression of diabetic foot. Common methods for monitoring microcirculation in the feet include the following:

3.1. Laser Doppler Flowmetry

Laser Doppler Flowmetry (LDF) is a commonly used non-invasive microcirculation monitoring technique that indirectly reflects tissue blood flow velocity by measuring the frequency changes of laser light scattered in tissues. As shown in Figure 2. One of the main advantages of the laser Doppler flowmeter is its non-invasiveness. It does not require punctures or the insertion of sensors; instead, it only requires the laser beam to be directed onto the skin surface of the measured area for real-time monitoring of microcirculation[8]. LDF provides real-time, continuous blood flow information and exhibits high sensitivity to dynamic changes in microcirculation. This is valuable for observing blood flow variations in physiological and pathological conditions, such as diabetic foot, trauma, and inflammation. LDF is also characterized by its high sensitivity, multi-area monitoring capability, and applicability to various animal models.
3.2. Ultrasound Color Doppler

Ultrasound Color Doppler is a medical imaging technique commonly used for measuring blood flow velocity and detecting vascular structures. This technology utilizes the Doppler effect of ultrasound, measuring changes in the reflected ultrasound wave frequency to obtain information about blood flow velocity [9]. As shown in Figure 3. Ultrasound Color Doppler has advantages such as being non-radiative, non-invasive, and providing real-time observations of dynamic blood flow changes. It is widely used in various medical fields, including angiography, obstetrics, neurology, and nephrology. Additionally, it holds significant importance in assessing the microcirculation status of arteries and veins in the feet. However, it relies heavily on the operator's skills and training, requiring the expertise of healthcare professionals for optimal use, with the quality of results being dependent on the operator's experience and proficiency.

![Figure 3. Doppler effect diagram](image)

3.3. Optical Coherence Tomography Doppler

Optical Coherence Tomography (OCT) technology was first proposed in 1991, with HUANG and colleagues in the United States being the pioneers in employing Optical Coherence Tomography imaging technology for imaging the human retina and coronary artery walls [10]. As shown in Figure 4. Optical Coherence Tomography Doppler is an advanced medical imaging technology that combines OCT with the Doppler effect. It is used for non-invasive visualization and quantitative assessment of vascular structures and hemodynamics distribution. OCT boasts excellent performance features such as high resolution, non-invasiveness, cross-sectional imaging capability, high sensitivity, and real-time imaging. It has rapidly developed applications in ophthalmology, cardiovascular studies, dermatology, and other fields. However, there are still challenges to overcome in OCT technology. Currently, commercially available intravascular OCT for clinical use can only achieve a line speed of approximately 100kHz, leading to distortion and blurring in 3D OCT images. Additionally, it is challenging to identify morphological structures at the cellular and subcellular levels.

![Figure 4. Schematic diagram of OCT system](image)

3.4. Photoacoustic Doppler

Photoacoustic Doppler is a biomedical imaging technology that combines optical and acoustic imaging. It uses momentary laser pulses to irradiate biological tissues, generating photoacoustic waves. As shown in Figure 5. The ultrasound signals caused by the absorption of laser energy in biological tissues are then detected. By analyzing these optical signals, structural and blood flow information of the tissue can be obtained. It possesses both the high resolution of ultrasound imaging and the high contrast of optical imaging. Compared to laser wide-field Doppler technology and optical coherence tomography Doppler technology, it can achieve imaging of deeper tissues [11]. This technology has broad prospects in the medical field, widely applied in the detection of cardiovascular diseases and cancerous tumors. However, there are still some issues to address. Firstly, when some photoacoustic probes receive laser pulses, the fluorescence phenomenon may consume a portion of energy, not fully converting the energy into photoacoustic signals, thus reducing the received photoacoustic signal intensity [12]. Additionally, many photoacoustic probes cannot self-decompose in the body, and ensuring their long-term decomposition in the body remains a challenge. Therefore, biodegradable photoacoustic probes will likely be a future development direction in the field of photoacoustic imaging.

![Figure 5. Schematic diagram of photoacoustic effect](image)

4. Surgical and Pharmacological Treatments for Diabetic Foot

Traditional treatment for diabetic foot primarily involves surgical interventions. Common surgical methods include tourniquet application, debridement, suturing, skin grafting, flap transplantation, and amputation/toe surgery, among others [13]. However, after surgical treatment, it is crucial to provide timely postoperative care for diabetic foot patients. This includes wound cleaning, infection...
prevention and control, vascular reconstruction, etc. These procedures require the attention of professional healthcare personnel, thereby increasing healthcare costs and the risk of postoperative infections.

Pharmacological treatment is also an essential component, primarily including hypoglycemic medications such as canagliflozin, metformin, dipeptidyl peptidase-4 (DPP-4) inhibitors, glucagon-like peptide-1 receptor agonists, etc. [14], antibiotics such as ampicillin + sulbactam, ticarcillin-clavulanic acid, amoxicillin+ clavulanic acid, and metronidazole-quinolone [15], medications targeting peripheral neuropathy such as alpha-lipoic acid, pregabalin, B vitamins, etc. [16]. While pharmacological treatment can significantly lower blood sugar and improve ulcers, there are also some drawbacks, such as canagliflozin potentially increasing the risk of leg and foot amputations [17], and excessive use of antibiotics at higher doses leading to antibiotic resistance in patients.

The pathological basis of impaired microcirculatory function includes atherosclerosis, thickening of capillary basement membranes, endothelial cell proliferation, and arterial luminal narrowing or obstruction. Although surgical and pharmacological treatments can indirectly alter microcirculation disorders in the lower limbs, the lower limbs, especially the wound areas of patients, are inherently fragile. External traction can easily cause more severe damage, increasing the risk of infection. Moreover, there are drawbacks such as a prolonged treatment period and significant drug side effects.

5. The Application of Physical Factor Therapy in Diabetic Foot

Currently, in addition to surgical and pharmacological treatments, physical factors are the most commonly used means in clinical practice. Physical factor therapy refers to the study and application of artificial or natural physical factors (such as electricity, light, sound, magnatism, heat, etc.) on the human body to improve health, prevent and treat diseases, and promote the recovery of the body after illness. Physical factors induce specific biophysical and physiological reactions, therapeutic effects, etc., in the human body through direct action, neural reflex action, and humoral action [18].

Physical factor therapy has advantages such as non-invasiveness, painlessness, minimal side effects, quick results, and lasting efficacy [19]. Physical factor therapy is non-invasive and can penetrate tissues at different depths. Especially for lower limb microcirculation, it can improve the blood flow velocity and perfusion of the foot, accelerating wound healing [20]. Most patients feel very comfortable during the treatment process, experiencing minimal discomfort as long as the procedures are strictly performed, contraindications are considered, and side effects such as discomfort or allergies are rare.

For treating diabetic foot, several common physical factor therapy methods are listed in Table 2 as follows:

### Table 2. Common physical factor therapy

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phototherapy</td>
<td>Non-invasive, easy to operate, short treatment time, and safe</td>
<td>The treatment mechanism is not yet clear. Excessive concentration can cause oxygen toxicity, decompression sickness, and other conditions.</td>
</tr>
<tr>
<td>Hyperbaric oxygen therapy</td>
<td>It has specific therapeutic effects for treating certain chronic hypoxic diseases.</td>
<td></td>
</tr>
<tr>
<td>Ultrasound Therapy</td>
<td>Accurate positioning, easy operation, high efficiency, and low treatment risk.</td>
<td></td>
</tr>
<tr>
<td>Acupuncture</td>
<td>High repeatability, economically simple.</td>
<td></td>
</tr>
</tbody>
</table>

5.1. Phototherapy

Phototherapy is an emerging physical therapy method in recent years that involves irradiating the affected tissues with low-level light therapy (LLLT) to achieve therapeutic goals through the photobiomodulation effect. This method has advantages such as non-contact, good patient compliance, clear efficacy, and safety [21]. Currently, the photobiomodulation mechanism involves accelerating the synthesis of DNA and RNA to promote cell proliferation. The specific principles include improving cell degeneration signals, regulating kinase activity, and adjusting intracellular cation concentrations, among other molecular biology effects. With the future development of laser technology and the reduction of treatment costs, LLLT is expected to become an excellent adjunctive treatment for chronic diseases [22].

Phototherapy can alter cell metabolism through the process of photodissociation. Inside cellular mitochondria, red light releases nitric oxide (NO) from cytochrome c oxidase (CCO). The oxidation-reduction reactions of CCO generate more adenosine triphosphate (ATP), producing additional reactive oxygen species (ROS) and activating DNA transcription factors like NF-kB and HIF-1. These transcription factors guide protein synthesis, and the resulting extra proteins play roles in cell proliferation, migration, and adhesion. As shown in Figure 6. This process enhances cellular activity, growth factor levels, and the regulation of inflammatory mediators, ultimately improving tissue oxygenation [22].

![Figure 6. Cellular mechanisms of LLLT](image-url)
Phototherapy has effects such as vasodilatation, anti-inflammatory properties, promoting tissue repair, and enhancing cellular energy metabolism. Infrared light can induce vasodilation, increasing blood flow. For patients with diabetic foot, especially those with microvascular complications, increasing blood flow is crucial for improving microcirculation in the feet. Additionally, near-infrared light and infrared light contribute to tissue repair and regeneration, aiding in the healing of diabetic foot ulcers and preventing infections.

5.1.1. Low-level laser therapy (LLLT)

Amir Haze et al. [24] used a low-level laser therapy device (B-Cure Laser) to irradiate patients with diabetic foot ulcers (DFU). B-Cure is based on a Ga-Al-As laser (Wavelength 808nm, Output Power 80mW). Among the 10 DFU patients receiving photobiomodulation (PBM) treatment, in addition to standard care, patients self-administered PBM irradiation to the wounds twice a day for 3 weeks. Another 10 patients were a blank control group and received necessary care daily. The results showed that 7 out of 10 patients in the PBM treatment group had wound closure rates exceeding 90%, while the blank control group had only 1 patient achieve a wound closure rate exceeding 90%. No adverse effects of the device were observed. This suggests that for patients with severe diabetic foot and complications, home-based low-level laser irradiation, in addition to standard care, is safe. However, this study did not provide an explanation for its mechanism, focusing solely on wound healing without observing relevant cellular changes.

R.K. Mathur et al. [25] conducted a study on 30 patients with type 2 diabetes mellitus using low-level laser therapy (LLLT) with a wavelength of 660nm and an energy density of 3J/cm². The study indicated that the LLLT group had a percentage reduction in ulcer area of 37±9%, while the control group had 15±5.4%. Furthermore, in the LLLT group, most wounds showed no purulent discharge and exhibited granulation tissue, whereas the control group, receiving conventional treatment, had more purulent discharge and less granulation tissue. This is attributed to the reduction in inflammation caused by photobiomodulation under LLLT, along with increased granulation tissue, fibroblast proliferation, collagen synthesis, and neovascularization. However, the study did not provide evidence for the underlying mechanisms.

5.1.2. Infrared Light

Yi Wang et al. [26] used the KP-220 infrared therapy instrument (Power 32mW/cm², Wavelength 2-25um) combined with methylcobalamin irradiation for diabetic foot patients. The control group received daily methylcobalamin injections, while the study group underwent infrared therapy in addition to the standard treatment for 4 weeks. The results showed that after treatment, both groups experienced a decrease in vibration sensation thresholds in the left/right lower limbs, with the study group significantly lower than the control group. Before treatment, there was no statistically significant difference in the conduction velocities of the left/right peroneal nerves and tibial nerves between the two groups. After treatment, the study group showed a significant increase compared to the control group. Before treatment, there was no significant difference in bFGF, VEGF, IL-6, TNF-α, and APN between the two groups. After treatment, both groups showed an increase in bFGF, VEGF, and APN, while IL-6 and TNF-α decreased. Moreover, the study group was significantly higher than the control group. In summary, infrared light combined with methylcobalamin therapy for diabetic foot can effectively improve lower limb nerve conduction velocity and vibration sensation thresholds, regulate serum levels of bFGF and VEGF, reduce the degree of inflammation, and contribute to the overall therapeutic effect of diabetic foot.

Min-Ling Chen et al. [27] investigated the application of wireless near-infrared spectroscopy technology to detect peripheral circulation changes in patients with diabetic foot ulcers. The aim was to study the reliability and effectiveness of near-infrared spectroscopy in detecting peripheral circulation changes while requiring patients to perform the Borg scale exercise. Patients were divided into Group A1 (with peripheral arterial disease, PAD) and Group A2 (without PAD). Additionally, 15 healthy participants were recruited as control Group B. Optical probes providing three wavelengths (640/700/910nm) were used to transmit light through the tissue and measure the foot's HbO2 and deoxy-Hb as the main indicators. The results showed that, before exercise, there was a significant difference in tissue HbO2 concentration between Groups A1 and A2. However, after exercise, no significant difference was found between Groups A1 and A2. Conversely, both before and after exercise, Groups A and B exhibited significant differences in HbO2 concentration. Near-infrared spectroscopy could effectively detect improvements in peripheral circulation, offering features such as non-invasiveness, continuous monitoring, accuracy, ease of use, and remote monitoring of lower limb circulation.

5.1.3. Polarized Light

Mona Mohamed Taha et al. [28] investigated the effects of polarized light therapy on the healing and microbial nature of diabetic foot ulcers. Eligible patients were randomly assigned to a phototherapy group receiving Bioptron light therapy (at a distance of 10 cm from the wound, wavelength 480-3400 nm, energy density 40 mW/cm²) in addition to standard wound care, and a control group receiving only standard wound care. The results showed a significant decrease in wound surface area and volume in both groups, with a more pronounced reduction and higher percentage decrease in the phototherapy group. There was also a significant difference in microbial populations, with a substantial decrease in positive microbial results in the phototherapy group after treatment. This could be attributed to two factors: firstly, polarized light may alter the surface properties of cell membranes and lipid-protein connections, affecting cell function and energy production; secondly, polarized light can enhance microcirculation and
increase the growth factors necessary for the formation of new blood vessels, thereby altering the healing process. This study demonstrates that polarized light is effective in promoting wound healing in diabetic foot patients and provides an explanation for its mechanism, making it a promising therapeutic approach.

5.2. Hyperbaric oxygen therapy (HBOT)

Hyperbaric oxygen, as an adjunctive therapy, has a history of nearly 50 years. For patients with diabetic foot ulcers, reduced vascularization resulting from diabetes promotes the development of these ulcers. Therefore, enhancing tissue oxygenation is crucial for the healing of chronic wounds, and intermittent oxygenation to hypoxic tissues can restore normal healing processes. The use of hyperbaric oxygen therapy in the human body can lead to increased tissue oxygenation, vascular constriction, activation of fibroblasts, reduction in inflammatory cytokines, upregulation of growth factors, enhanced antimicrobial effects, improved antibiotic efficacy, and reduced leukocyte chemotaxis[29]. Simultaneously, the primary intervention principle of hyperbaric oxygen therapy is to increase the oxygen content in the patient's body tissues, correct the hypoxic state of the wound, thereby improving tissue microcirculation. It can also accelerate capillary angiogenesis, establish collateral circulation, and elevate the levels of blood supply and perfusion[30].

In a normal wound, macrophages combat wound bed pathogens, while fibroblasts deliver VEGF to initiate regrowth of epithelial cells and close the open wound. In diabetic wounds, insufficient angiogenesis and macrophage function result in significant pathogen invasion, while lower fibroblast presence delays re-epithelization and wound closure. Adapted with permission. As shown in Figure 7.

Figure 7. Mechanisms of normal versus diabetic wound healing

Pasek Jaroslaw et al.[31] investigated the efficacy of local hyperbaric oxygen therapy in treating diabetic foot ulcers. The study included 45 patients, comprising 24 males and 21 females. Oxygen therapy was conducted at a pressure of 2.5 atmospheres absolute (ATA) for a total of 30 sessions, each lasting 30 minutes. The results indicated a significant reduction in wound surface area after treatment, with complete healing observed in 5 patients and a notable 50% decrease in the local status of wound surfaces in 25 patients. The Visual Analog Scale (VAS) pain perception also significantly decreased in all examined patients. Consequently, it was concluded that local hyperbaric oxygen therapy could expedite ulcer healing in the treatment of diabetic foot ulcers and reduce the intensity of perceived pain. However, this clinical trial lacked a control group, potentially leaving other factors influencing wound healing unaccounted for. Additionally, there was no follow-up conducted to confirm the patients' later-stage recovery.

Chen Zhenzhen et al.[32] conducted a systematic review and meta-analysis to explore the efficacy and safety of hyperbaric oxygen therapy in patients with diabetic foot ulcers (DFU). The study involved literature screening, data extraction, and bias risk assessment, followed by meta-analysis using RevMan 5.4 software. The primary outcome measure was the complete healing rate, and secondary outcome measures included the effective rate, major amputation rate, minor amputation rate, reduction in ulcer area, and frequency of adverse reactions. The treatment group received basic treatment plus hyperbaric oxygen therapy, while the control group received basic treatment or basic treatment plus hyperbaric air. The results indicated that the effective rate in the hyperbaric oxygen group was superior to that in the control group and exhibited good stability. Regarding the improvement of major and minor amputation rates, there was insufficient evidence to prove that the addition of hyperbaric oxygen therapy could reduce the occurrence of major and minor amputation events. The hyperbaric oxygen treatment group showed a reduction in ulcer area compared to the control group. The comparison of adverse event rates across studies did not yield statistically significant differences. In conclusion, hyperbaric oxygen therapy significantly improved the complete healing rate and effective rate in patients with DFU, promoting the healing of diabetic foot ulcer wounds with good safety. However, the study has limitations such as substantial bias and a small sample size, suggesting the need for further refinement of the diabetic foot assessment system and clarification of the target population to benefit DFU patients.

5.3. Ultrasound Therapy

Research on the bioacoustic effects of ultrasound continues to evolve. One of the main mechanisms of ultrasound is achieved through the cavitation process, which involves the local, unidirectional flow of liquid around it. This very small liquid flow is known as microstreaming and plays a crucial role in ultrasound therapy[33]. Additionally, ultrasound debridement has become a common method for treating diabetic foot wounds in recent years. It utilizes the cavitation effect of ultrasound in the flushing jet. After the collapse of cavitation bubbles, pressures up to 1000 atmospheres and microjets are generated rapidly and effectively clearing bacteria and fungi from the surface and deep tissues of the wound. It also aids in washing contaminants from infected wounds, contributing to wound healing and improving microcirculation[34]. Recently, there has been a shift towards using low-frequency ultrasound in the kilohertz range to achieve vasodilation and bone healing.
William J. Ennis and colleagues\cite{35} conducted a study on the effectiveness of ultrasound therapy for diabetic foot ulcers. The selected 133 patients were randomly divided into an ultrasound treatment group and a control group. The ultrasound treatment group received treatment using a non-contact ultrasound device (operating frequency of 40 kHz, treatment intensity ranging from 0.1 W/cm² to 0.5 W/cm²) and standard wound care. The control group only underwent standard wound care. Both groups received treatment three times a week for 4 minutes each time, totaling 12 weeks. Wound assessments, including evaluations of granulation tissue, fibrous protein, scab area, and skin, were conducted weekly. The results showed that 40.7% of wounds in the ultrasound treatment group healed, while only 14.3% of wounds in the control group healed. Moreover, there was a significant difference in the healing time between the two treatment groups, with an average healing time of 9.12 weeks in the ultrasound treatment group compared to 11.74 weeks in the control group. Ultrasound therapy has been proven to be a useful adjunctive method for treating diabetic foot ulcers, characterized by its non-invasiveness, safety, good patient tolerance, and ease of management.

Di Haiping and colleagues\cite{36} observed and investigated the bacterial clearance effects and the impact on microcirculation of ultrasound debridement and smart negative pressure wound therapy technology in diabetic foot ulcer wounds. Seventy-six diabetic foot patients were selected as the study subjects and randomly divided into two groups. The observation group received treatment with ultrasound debridement combined with smart negative pressure wound therapy pump, while the control group received treatment with ultrasound debridement combined with conventional gauze dressing changes. The study compared the ulcer wound healing effects, bacterial quantification, transcutaneous oxygen partial pressure, and wound blood perfusion between the two groups. The results showed that there were statistically significant differences in ulcer wound healing effects and recurrence rates between the two groups ($P < 0.05$). After 14 days of treatment, there were significant differences in bacterial quantification, transcutaneous oxygen partial pressure, and wound blood perfusion between the two groups ($P < 0.05$). Thus, the combination of ultrasound debridement and smart negative pressure wound therapy technology can aid in the healing of diabetic foot ulcer wounds, significantly improve bacterial clearance, and simultaneously alter microcirculation, demonstrating good clinical application value.

### 5.4. Acupuncture

The treatment of diabetic foot primarily involves the application of antibiotics, vasodilators, metabolic control, and promoting blood circulation to remove blood stasis. However, the efficacy is not remarkable. Western medical treatments often fail to achieve satisfactory results. In contrast, the use of traditional Chinese medicine in treating diabetic foot presents significant advantages, such as enhancing patients' mental well-being, reducing medical costs, and alleviating pain. Warm needle acupuncture, utilizing the warming stimulation from moxibustion, can promote blood circulation, eliminate dampness, and reduce swelling, thereby improving the blood circulation in the lower limbs affected by diabetic foot. Acupuncture therapy offers notable advantages, including high repeatability and cost-effectiveness, making it an important method in traditional Chinese medicine with satisfactory outcomes in the treatment of diabetes.

Li Bing\cite{37} investigated the efficacy of warm needle acupuncture as an adjunctive treatment for diabetic foot patients and its impact on serum IGF-1 and MMP-9. Conventional treatments for diabetic foot patients, such as pioglitazone, can significantly dilate blood vessels and effectively improve vasospasm, but the therapeutic effect is still limited. Traditional Chinese medicine views this condition as a progression from prolonged thirst, with pathogenic factors involving blood stasis, malnourishment in the limbs, and differences in signs of heat and cold. Patients were divided into two groups: the control group and the observation group. Both groups received regular diabetes treatment, with the observation group receiving additional warm needle acupuncture. The results showed that the cure rate in the observation group was significantly higher than that in the control group ($P < 0.05$), and the blood flow in the observation group was significantly greater than that in the control group ($P < 0.05$). After treatment, both groups showed an increase in serum IGF levels and a decrease in MMP-9 expression. However, the change values of IGF and MMP-9 in the observation group were significantly higher than those in the control group ($P < 0.05$). The elevation of IGF has an important promoting effect on wound healing, while the increased expression of MMP-9 can make it difficult for ulcer wounds to form scar tissue. Therefore, warm needle acupuncture treatment can effectively unblock local Qi and blood meridians in patients, leading to precise therapeutic effects.

Wang Zengmin et al.\cite{38} studied the clinical efficacy of acupuncture combined with conventional drug treatment for diabetic foot. A total of 100 eligible diabetic foot patients were selected and randomly divided into a control group and an observation group, with 50 cases in each group. The control group received conventional Western medical treatment, while the observation group received acupuncture treatment in addition to the control group's treatment. The results showed that the total effective rate in the observation group was significantly higher than that in the control group ($P < 0.05$). After treatment, the bFGF level in the observation group was significantly lower than that in the control group ($P < 0.05$), while the IGF-1 and VEGF levels were significantly higher than those in the control group ($P < 0.05$). The observation group had a significantly shorter wound healing time ($P < 0.05$) and a significantly higher wound healing rate than the control group ($P < 0.05$). In summary, acupuncture combined with conventional drug treatment for diabetic foot significantly improves therapeutic effects, but the safety of this approach was not elucidated.
6. Conclusion

In summary, microcirculation disorders are the fundamental cause of diabetic foot, and early detection and intervention can effectively prevent the occurrence and development of diabetic foot. Currently, laser Doppler technology can be applied for real-time monitoring of blood flow perfusion in larger tissue areas, which is of great significance for assessing the microcirculation of foot arteries and veins. However, there are certain limitations in terms of measurement accuracy, product integration, and measurement depth. Physical factors provide a guarantee for microcirculation intervention and improvement. Among them, phototherapy has a good biological regulatory effect on the treatment and recovery of diabetic foot and is a promising therapeutic method. Based on this, developing non-invasive phototherapy devices that are safe, effective, affordable, and portable/wearable for diabetic foot could be a future direction for phototherapy in this field. Phototherapy, compared to other physical stimuli, has advantages such as non-invasiveness, simplicity of operation, and suitability for patients. However, there are still challenges, including unclear mechanisms of action, limited clinical examples, and unclear dose-response relationships. With the accelerated aging of the population in China and diabetes becoming one of the most prevalent diseases, diabetic foot, as one of the most severe complications with the highest incidence among diabetes patients, will have significant clinical and social implications if further research is conducted on the mechanisms and clinical experiments of phototherapy for diabetic foot.

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