APPLICATION OF WEFT-KNITTED SPACER FABRICS AS ABSORBENT DRESSINGS FOR EXUDING WOUNDS

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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CERTIFICATE OF ORIGINALITY

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_____ (Signed)

_____Yang Yadie_____(Name of student)

To my parents

For their love and support

Abstract

Exuding period is a crucial but hard to manage period of a deep injured wound or burn. An ideal dressing for exuding wound requires quick and large absorbency, good thermal property, moisture management, air permeability and mechanical property. Fast wicking property and high absorbency help dressing to absorb all exudate immediately and avoid maceration of surrounding skin. This reduces the change frequency of wound dressing and the possibility to disturb the wound. The moisture should be managed in a certain range to keep wound physiologically moist, neither dry nor covered in fluid. In addition, dressing should be oxygen permeable to accelerate wound healing by promoting fibroblast proliferation and collagen synthesis. High heat keeping rate is required for maintaining the wound in a normal body temperature, which allows optimal cellular function. Furthermore, when applying on a wound, dressing should adapt to the body shape of the wound site. Currently commercial dressings for heavily exuding wounds still have some drawbacks, such as poor integrity, slow wicking property, poor air permeability, a need of secondary dressing and very high price.

Spacer fabrics can well overcome these drawbacks and maximize their performance as dressing material. In this study, spacer-fabric-based dressing was firstly designed according to the requirements of exuding wound care. Three layers were included in the designed dressing. The wound contact layer should be a hydrophobic with quick moisture transmission rate, and the outer layer should be waterproof to protect the

wound. Therefore, its two surfaces were produced with elastic synthetic yarns, and the spacer layer were knitted with absorbent yarns. Twelve different spacer fabrics were produced and their properties were assessed. Considering their good air permeability and appropriate absorbency and WVTR, spacer fabric knitted with cotton spacer yarn and with 4 needle connecting distance was selected as the basic material of the designed dressing.

Then, the selected spacer fabric was processed with antibacterial treatment. A silver-containing spacer fabric was manufactured and analyzed. The silver distributions were compared between the spacer fabric and 4-layered cotton fabric. The results show that spacer fabric could keep the silver ions in the middle layer, the bacteria would be killed in the middle layer of dressing. The way to absorb wound exudates and kill bacteria within the dressings reduces silver concentration on the wound bed, and therefore this could be an efficient way to lower the potential of silver entering human body, and prevent the silver toxicity and wound-healing delay.

As wound dressing should keep contaminated fluid and harmful substance away from the wound, water resistant treatments were carried out on spacer fabric surface. The aims of these methods were not only to make the spacer fabric water resistant but also to keep the good air permeability of spacer fabric. In this regard, three kinds of air permeable water resistant treatments were applied including treatment with electrospun nanofibrous polyurethane or polystyrene membrane, treatment with

fluorocarbons agent NUVA N2114 and treatment with TiO_2 nanosol. The treated spacer fabrics were evaluated by the water contact angle test and air permeability test.

The spacer-fabric-based dressings were compared with three types of commercial dressings to evaluate their performance while using as absorbent dressings for exuding wounds. Different performance indicators including the wettability, absorbency, moisture transmission, air permeability, extensibility and water contact angle tests were tested. As a result, the spacer-fabric-based dressings could absorb large amount of fluid in a short period, and they were permeable for air and moist vapor while they were tended to keep a moist environment with low evaporation after absorbing.

The biocompatibility and wound healing property of spacer-fabric-based wound dressing were evaluated by *in vitro* cytotoxicity study, animal intracutaneous reactivity study and *in vivo* wound healing study. The spacer-fabric-based dressing was considered no cytotoxicity potential on L929 mouse fibroblast cells. Also, the animals did not show any grade of erythema or edema after intradermal injection of the dressing extracts. In addition, the *in vivo* wound healing test showed that spacer-fabric-based dressing accelerated full thickness wound healing when comparing with cotton gauze. Spacer-fabric-based dressing can be a promising wound care product to facilitate wound healing.

List of Publications Arising from the Thesis

Refereed Journal Papers

1. Yadie Yang and Hong Hu. Application of superabsorbent spacer fabric as exuding wound dressing. *Polymers*. 2018, 10(2):210.

2. Yadie Yang, et al. A novel silver-containing absorbent wound dressing based on spacer fabric. *Journal of Materials Chemistry B*. 2017, 5(33): 6786-6793.

3. Yadie Yang and Hong Hu. Spacer fabric-based exuding wound dressing-Part I: Structural design, fabrication and property evaluation of spacer fabrics. *Textile Research Journal*. 2016, 87(12), 1469-1480.

4. Yadie Yang and Hong Hu. Spacer fabric-based exuding wound dressing-Part II: Comparison with commercial wound dressings. *Textile Research Journal*. 2016, 87(12), 1481-1493.

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Chapter 1 Introduction

1.1 Motivation of the research

The market potential for wound care has continuously increased in recent years. In particular, the growth and aging of the population are driving the demand for wound dressings with multi-functions [1, 2]. Medium to heavily exuding often appears in the middle period of a deep injured wound or burn. This is a critical period which is difficult to be managed [3]. Since George Winter [4] found that occlusive dressing facilitated epithelialization in porcine wounds, the principle of maintaining a moist wound environment has been accepted for decades. Opposite to the traditional concept that a wound should be dry to form a scab and to promote healing, a wet environment instead can lead to maceration and tissue breakdown to allow a wound heals faster [5]. Based on this principle, sophisticated dressings which could provide moist, absorbent, interactive and non-toxic environments for wound healing have been developed [6].

Conventionally, cotton gauze is applied to wounds because they are soft and flexible and have a good absorption property. However, cotton gauze allows moisture to evaporate from the wounds, making them dry without maintaining a moist environment for facilitating wound healing. In addition, cotton gauze is easily adhere to the wound and require frequent changes, causing trauma and pain to patients [7-9].

For heavy exudate wounds, foam dressings and alginate dressings are often used because they are highly absorbent. Foam dressings are generally made from hydrophilic polyurethane foam and have different absorption rates depending on their composition and thickness [10]. Highly absorbent foams may reduce the frequency of dressing change. Some absorption capacities can be up to seven days. Mixed cell foam with increased speed of fluid uptake provides cushioning and protection, and fast absorption and vertical wicking to reduce the risk of maceration to the adjacent tissue. Nonetheless, the prices of commercial foam dressings are very expensive, usually dozens of times higher than normal cotton gauze, which limits their utilization, especially in developing areas [11].

Alginate wound dressings are non-woven materials made of soft fibers derived from brown seaweed. When placed within the wound bed, alginate dressings react with serum and exudate via exchanging sodium ions with calcium ions exuded from the wound [12]. The ion exchange with exudate forms a fibrous gel, which can provide a moist and warm wound environment. As alginates are highly permeable and non-occlusive, a secondary dressing is normally required. The most commonly used secondary dressing is gauze [13-15]. However, the majority of alginate dressings may trap bacteria, often giving rise to wound malodor and bringing an unpleasant experience to patients.

An ideal dressing should provide a moist and warm environment on the wound surface, and at the same time can provide a barrier against microorganisms, dirt and other foreign bodies. In addition, it can remove exudate and be able to be removed without disturbing new tissue growth [16]. A modern wound dressing applied to exuding wounds normally consists of three layers, namely, a wound contact layer, an absorbent layer, and a barrier surface layer, where the absorbent layer is sandwiched between the other two layers. While the absorbent layer uptakes exudates, blood and other body fluids, the wound contact layer should be non-adherent and easy removal without additional trauma of the wound [8, 17-19].

The main limitations of the currently available dressings for heavy exudate wounds can be summarized as follows [3, 17, 19-21]: (i) The majority of high absorbent dressings are made of foams, alginate, hydrogel, hydrocolloid, etc., and cannot retain their original shape or integrity during the use. Therefore, cleaning or washing to remove the remnants of such dressings left in the wound is required ; (ii) Wound malodor is partially caused by heat generation from skins and poor air permeability; (iii) Low extensibility reduces the comfort when applied to a joint or a region of movement of the body; (iv) Limited shapes and sizes lead to dressing fit less compactly; (v) Some of them are adherent to the wound, causing trauma and pain on removal; (vi) The costs involved are high.

Spacer fabrics can well overcome the above-mentioned drawbacks and can maximize their performance as dressing material. Spacer fabrics are a type of 3D textile structure in which two outer fabric layers are connected by a layer of spacer yarns [22, 23]. The 3D nature of spacer fabric structure makes them an ideal candidate for this kind of application [24]. Spacer fabrics are breathable with high air permeability, which is important to odor removal. They have good ability to control heat and moisture transfer, keeping moist and thermal insulating environment for wound healing. Spacer fabrics are soft, while having good resilience that can provide a good cushioning effect to the body [25] and good distribution of pressure [26]. An important advantage of spacer fabrics is that the knitted structures can be adjusted according to different requirements of absorbency and water vapor permeability, to adapt to different types and stages of exuding wounds. These changes on spacer fabrics can be easily and cost-effectively realized through rearranging the spacer yarn connecting distance, number of elastic yarns and type of spacer yarn or other structure factors.

Although some compression bandages were developed based on spacer fabrics, little application for absorbent dressings using spacer fabrics have been reported. Some applications of spacer fabrics as compression bandage or absorbent medical bandage only focused on compression or absorbency, rather than moisture management, anti-microbial and biocompatibility [27, 28]. Until now, spacer fabrics particularly

designed and fabricated for wound dressing with high liquid absorption and retaining are still needed.

1.2 Objectives

This study aimed to accelerate exuding wound healing by designing and fabricating a new type of wound dressing based on spacer fabric as a substitute of the currently used wound dressings. The details of the objectives are as follows:

a) To design the spacer-fabric-based dressing which can meet the requirements of an ideal absorbent dressing including short wetting time, good absorbency, moist keeping, comfort, antimicrobial and biocompatibility.

b) To fabricate spacer fabrics with different materials and structures and select the suitable spacer fabric for applying as wound dressing.

c) To enhance the antibacterial property of spacer-fabric-based dressings by padding the whole spacer fabric with antibacterial agents.

d) To improve the waterproof properties of the outer surface of spacer-fabric-based dressing by electrospinning or coating a layer of porous and permeable membrane on the surface of spacer fabrics.

e) To assess the performance of spacer-fabric-based dressings by comparing them with commercial absorbent dressings such as foam dressings and alginate dressings.

f) To test the wound healing speed *in vivo* and confirm the biocompatibility and safety of the spacer-fabric-based dressings.

With the successful completion of this study, the spacer-fabric-based wound dressing with high liquid absorption and moist retaining, and good anti-microbial property and biocompatibility can be developed. It is helpful to promote the exuding wound healing and the application of spacer fabric in medical area.

1.3 Methodology

The purpose of this study was to design and fabricate a new type of exuding wound dressing based on spacer fabric to help wound healing. The spacer fabric should be absorbent, while its outer surface should be waterproof. The spacer-fabric-based dressing should be anti-microbial and have low cytotoxicity. In accordance with the specific objectives, different experimental approaches were adopted. As many machines, materials and testing standards were used in this study, the details will be given in each chapter. The procedures in Figure 1.1 summarize the methodology.

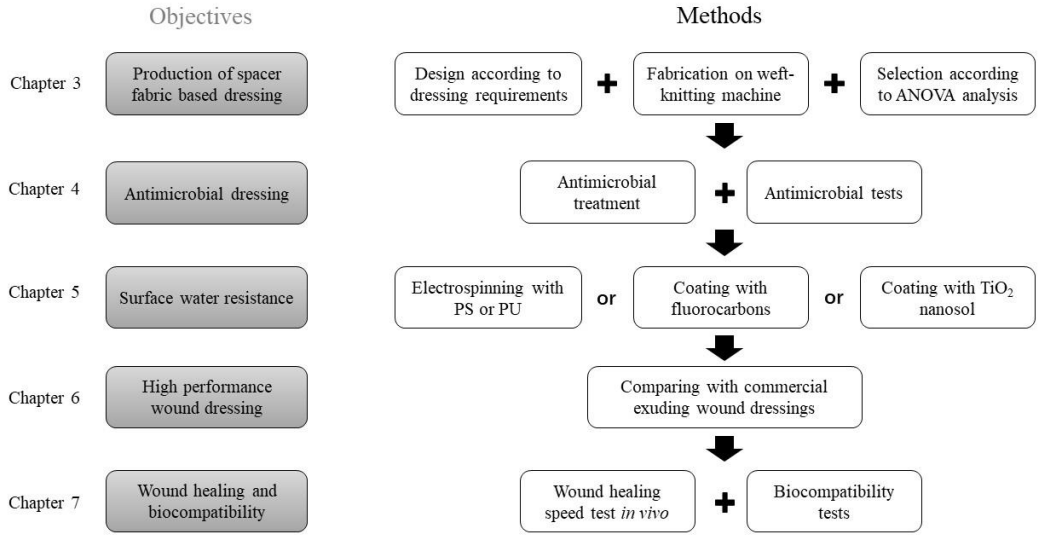


Figure 1.1 Procedures of application spacer fabric as exuding wound dressing.

a) Design and fabrication of spacer-fabric-based dressing

A multi-functional dressing based on 3D spacer fabric was designed according to the requirements of exuding wound dressing. The outer layer was designed to be waterproof to protect the wound from contaminated fluids. The middle layer was to quickly absorb and retain exudate, and therefore, the middle layer was designed to be knitted with absorbent yarns. The wound contact layer should be hydrophobic. The whole dressing should be antibacterial and biocompatible.

Weft-knitting was applied to fabricate spacer fabric in this study. The outer layer and wound contact layer were single jersey structures knitted with single or double polyester/spandex yarns. The spacer layer was knitted with cotton or Tencel yarns using different spacer yarn lengths. Statistical analyses were conducted and the

optimal structure of spacer fabrics was selected according to the wettability, absorbency, permeability and thermal property.

b) Antibacterial treatments

The antibacterial treatments of spacer-fabric-based dressing were conducted to make them safe to the wound. Two kinds of antimicrobial agents, silver and ammonium were adopted. The whole spacer fabric were impregnated in the antimicrobial agent and then padded by a padder. To evaluate antimicrobial property of the treated spacer fabric, reductions in viability were observed for both the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae*.

c) Water resistant treatments

To enhance the water resistance of the outer layer of dressing with good permeability, three kinds of water resistant treatments were applied to the selected spacer fabric. The first method was to cover a permeable polystyrene (polystyrene) or polyurethane nanofibrous membrane on the outer layer of spacer fabric by electrospinning process. The second method was to coat the commercial water resistant agents on the outer surface of spacer fabric. The third method was to spray TiO_2 containing sol on the fabric surface to improve the water resistance. Characterization and water resistant tests were carried out after treatments.

d) Performance assessment and comparison with commercial absorbent dressings

In order to confirm the performance of the spacer-fabric-based dressing developed, they were compared with commercial absorbent dressings including foam dressing and alginate dressing. The most important properties including wettability, absorbency, water resistance, air permeability and fluid handling capacity were evaluated and compared.

e) Wound healing and biocompatibility

Both *in vitro* and *in vivo* experiments were carried out to evaluate the wound healing property of the spacer-fabric-based dressing. The biocompatibility tests including cytotoxicity and irritation and skin sensitization tests were implemented. The cytotoxicity test aimed to confirm the cell attachment characteristics and nontoxicity of the spacer-fabric-based dressing. The irritation and skin sensitization was evaluated for the potential to cause irritation following intracutaneous injection in rabbits. The wound healing speed was tested when applying spacer-fabric-based dressing *in vivo*.

1.4 Significance and values

The particularly designed and fabricated antibacterial absorbent dressing based on spacer fabric had ideal dressing properties to promote the wound healing. Spacer fabric has great potential to be applied as exuding wound dressing, and the lack of related

study made this work significant. All body liquids emitted from the wound could be entirely absorbed by the dressing and the retention of body liquids sustains a moist environment for wound healing. The moist environment has been widely accepted to be a satisfied environment for wound healing, rather than dry or immersion environments. The dressing had a relatively low water vapor permeability which is necessary and crucial because fluid inside a dressing has great effects on water vapor permeability and moist healing environment. The spacer fabric had an advantage in keeping a moist environment for wound, which is one of the most important things for an absorbent dressing. With the comparable absorbency, the spacer fabric had much better air permeability than foam dressings. Anaerobic bacteria are one of the main causes for wound malodor when severe colonization or infection happens. A permeable antimicrobial wound dressing allows oxygen in and kill the bacteria. As a result, the amounts of anaerobic bacteria could be reduced and the wound malodor could be eased.

This study provided methods to fabricate spacer fabric with different functions in different layers. Combining 3D weft-knitted spacer fabric and functional treatments was a new method in developing medical textiles. Different finishing methods has been developed to produce multi-functional spacer fabric. The dressing surface was treated with electrospinning or spray coating methods, and spacer fabric was treated with antibacterial agents by padding method. Seldom finishing on spacer fabric has

been researched before. This study gave an example of chemical finishing on spacer textiles.

The parameters of spacer fabric knitting processes and finishing processes can be adjusted to adapt different types of wounds, which may become important guidance or reference for the following research and manufacturing. This study may improve the development of textile technology in medical application and encourage scientists to discover new ways to apply textiles in healthcare.

1.5 Thesis outline

Chapter 2 reviews the relevant literatures to present the achievements and limitations of earlier work in relevant areas. This improves the general understanding of the background, and illustrates research gaps and significances of this study.

The overview contents from Chapter 3 to Chapter 7 are shown in Figure 1.1.

Chapter 3 focuses on the design and fabrication of the spacer-fabric-based dressing. The design was based on the requirements of an ideal absorbent wound dressing. According to the requirements, the wetting property and permeability of materials, the arrangements of yarns and the antibacterial treatments and waterproof treatments were

considered. An antibacterial dressing with waterproof surface and good absorbency and permeability has been designed. Twelve different types of spacer fabrics and their properties, including wettability, absorbency, permeability, and thermal insulation are presented. The results of a statistical analysis are shown to evaluate the effects of structural and yarn parameters on the properties of the spacer fabrics. Based on the testing results, the selection of suitable spacer fabrics for wound dressing material are given.

Chapter 4 illustrates the antimicrobial treatment with silver and the working principle of silver-containing spacer fabric. The silver distribution on spacer fabric and layer-by-layered fabric was investigated. The antimicrobial property was tested according to the reductions in viability for both the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae*. The unique three-dimensional spacer fabric could keep most of silver in its middle layer and kill bacteria in the middle layer rather than the wound contact surface.

Chapter 5 describes three kinds of water resistant methods to treat the selected spacer fabric, including treatment with electrospun nanofibrous membrane, fluorocarbons and TiO_2 nanosol. The aims of these methods are not only to make the spacer-fabric-based wound dressings waterproof, but also to keep the good air permeability.

Chapter 6 focuses on dressing property assessment and comparison with commercial absorbent dressings. In order to confirm the performance of the spacer-fabric-based dressing developed, it was compared with commercial absorbent dressings including foam dressing and alginate dressing. The important dressing properties including wettability, absorbency, water resistance, air permeability and fluid handling capacity were evaluated and compared.

Chapter 7 contains *in vitro* and *in vivo* experiments to evaluate the biocompatibility and wound healing property of spacer-fabric-based wound dressing. The cytotoxicity was tested by confirming the cell attachment characteristics and nontoxicity of the dressing. The irritation and skin sensitization test was carried out for the potential to cause irritation following intracutaneous injection in rabbits. The wound healing speed was tested when applying spacer-fabric-based dressing *in vivo*.

Chapter 9 presents general conclusions, contributions, limitations, and suggestions for future work.

Chapter 2 Literature review

2.1 Introduction

This chapter reviews the relevant literature and presents the research gap of this study. First the wounds and wound healing process are covered, including the moist wound healing principle and the effects of exudates for wound healing. Then the requirements of exuding wound care and the currently used absorbent dressings are summarized. The main limitations of the currently available dressings for exudate wounds have been summarized. Finally, the previous studies on spacer fabrics are reviewed and the capabilities of applying spacer fabric as absorbent wound dressing are discussed.

2.2 Wounds and wound healing process

Skin is the largest organ in the human body, which plays a crucial role as a protective barrier to the external environment, preventing external noxious agents such as bacteria and viruses and maintaining the internal environment through the regulation of water and electrolyte balance and thermoregulation. It is crucial to keep its integrity, as these functions are no longer adequately performed when this barrier is disrupted and damaged due to any cause (mechanical injuries, ulcers, burns, neoplasm or surgical trauma) [29, 30].

2.2.1 Types of wounds

A wound is defined as a defect or a breakdown in the protective function of the skin[31]; the injury in the epithelial integrity of the skin or underlying tissues/organs resulting from physical or thermal damage including surgery, cuts, scratches, pressure, burns, puncture and immunodeficiency or disease [29, 32]. The severity of a wound depends on diameter and depth of the wound and the damage caused in the epidermis and dermis layers of the skin [8, 33]. It takes several days or weeks for a wound healing process which ends with wound closure [34, 35].

Many ways have been used to classify wounds and there is no standard classification for wounds. According to the healing duration of a wound and the nature of the repair process, it can be classified as acute or chronic. Acute wounds usually happen in a short time, heal rapidly and can be predicted by the repair process [36]. Most of them heal completely and uneventfully resulting in durable closure with minimal scarring and no complications, in 8 to12 weeks [30, 31]. Acute wound fluid helps to stimulate fibroblasts and to produce endothelial cells which contain rich leukocytes and essential nutrients [37, 38]. This presents as serous fluid in the wound bed and support the normal wound healing process in acute wounds [3]. Acute wounds are usually traumatic or surgical tissue injuries [36].

The healing process and pattern of the chronic wound are different from acute wounds. Chronic wounds are difficult to heal or take a long time to heal and might have some complications [39]. It is caused by the defective remodeling of the ECM, which is a result of the failure to re-epithelialize and reduction of growth factors [6, 40-42]. In addition, chronic wound fluid has high levels of proteolytic enzymes having an adverse effect on wound healing by interfering cell proliferation, particularly of keratinocytes, fibroblasts and endothelial cells [6, 43]. With this understanding of these differences between the acute and chronic wound, principles of selecting different dressing methods are established. To convert chronic wounds to acute wounds is a possible way to healing chronic wounds in a short period.

2.2.2 Wound healing process

The healthy skin and underlying tissues can be divided into five major parts as shown in Figure 2.1: epidermis, corium, subcutis, fascia and muscle [37]. When skin suffering from a mechanical injury or irritation or some disease, a breach with certain width and depth will occur on the skin. To make this breach contracted and then occlusive is the process of a wound healing.

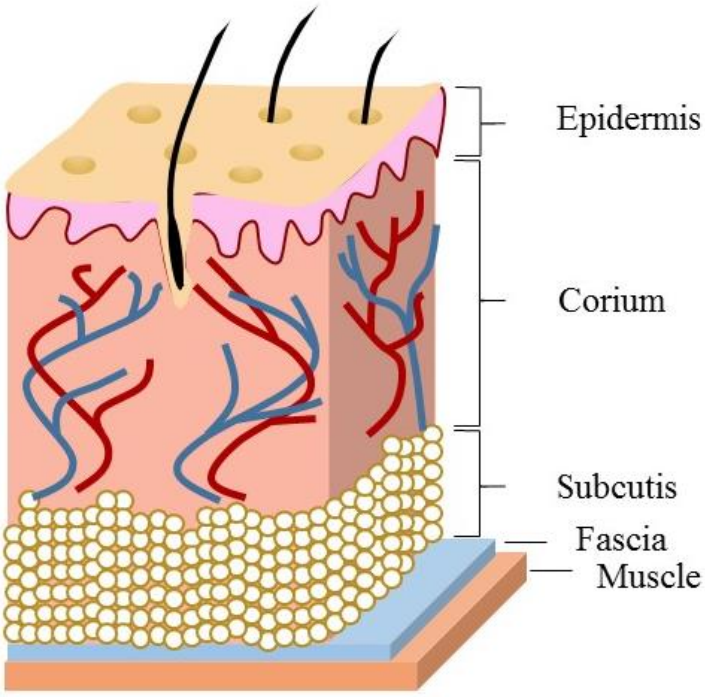


Figure 2.1 The structure of the skin.

Wound healing is a dynamic and complex process. Simply, the wound healing process is a general phenomenon of growth and tissue regeneration. For the normal wound involve a series of coordinated events, including bleeding, phagocytosis, chemotaxis, coagulation, initiation of an acute inflammatory response to the initial injury, regeneration, migration and proliferation of connective tissue and parenchyma cells, as well as synthesis of collagen and extracellular matrix components, remodelling of new parenchyma and connective tissue and collagen deposition [44].

The current wound healing model consists of four general phases [45-50]: (i) the coagulation and haemostasis phase, which begins immediately after injury; (ii) the

inflammatory phase, which occurs shortly after injury to tissue and during which swelling takes place; (iii) the proliferation period, in which new tissues and blood vessels are formed; (iv) the maturation phase, in which tissues laid down during the proliferation stage are remodelled. These activities occur in an ordered manner overlapping with each other, and they are in a well-connected cascade [51, 52]. The overlap of these stages of healing is illustrated in Figure 2.2. The entire process can last for many months.

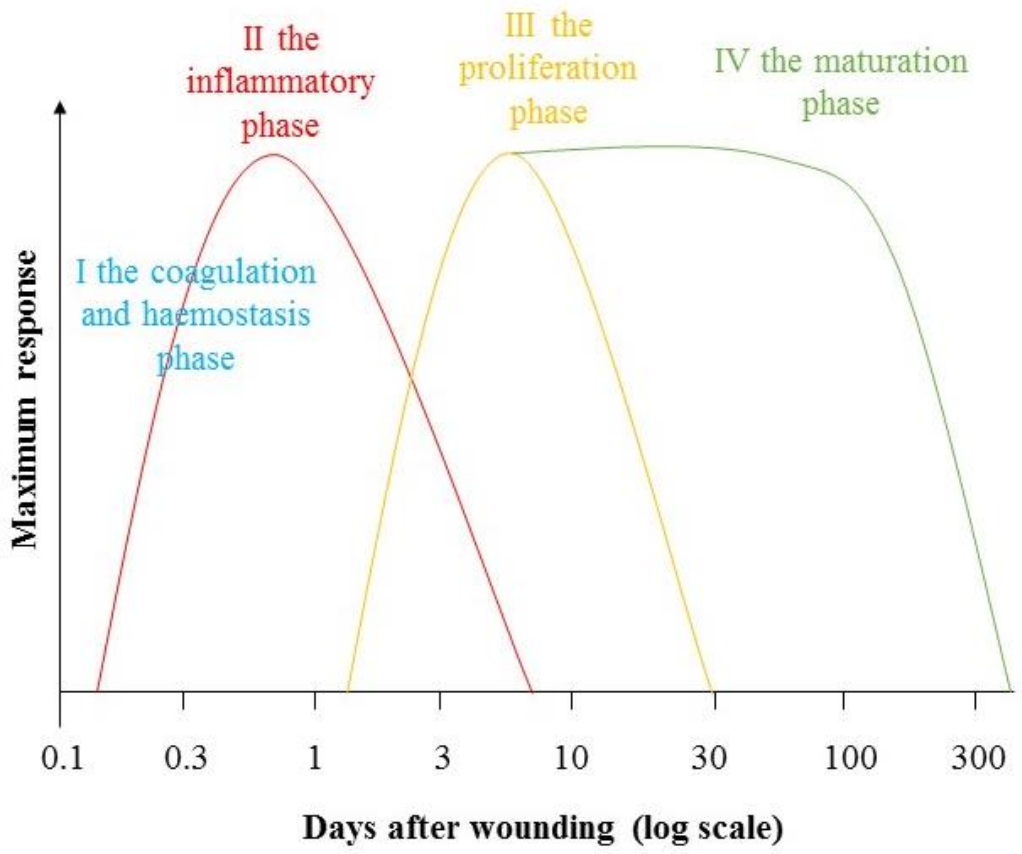


Figure 2.2 Phases of repair in normal wound healing.

The appearance of the wound in the four phases may change from black to yellow, then red and finally pink. The four colors to some extent overlap with the above four healing phases, but they are not identical. Table 2.1 summarizes the clinical manifestation and wound care methods of different phases in wound healing process.

Table 2.1 Four phases of wound healing process.

Periods of wound healing process	Black period	Yellow period	Red period	Pink period
Clinical evaluating	Eschar-black/brown necrotic tissue, can be hard or soft, with or without light exudate	Slough-yellow, tan dead tissue (devitalized), moderate exudate	Red, cobblestone appearance (healing, filling in), heavy exudate (decreasing)	Epithelization, dimension reduction, less exudate
Aims of wound care	To remove eschar	To clear decayed tissue	To absorb exudate, keep moist wound environment, and accelerate granulation	To protect new epithelial tissue
Recommended wound dressings	Hydrogel	Hydrogel and films/foam dressing	Foam dressing, alginate dressing	Films dressing

Table 2.1 shows that the red period has the most heavily exuding. The absorbent wound dressings are recommended according to the moist wound healing principle which was initially discovered by Since George Winter in 1962 [4]. He found that occlusive dressing facilitated epithelialization in porcine wounds, and therefore he

concluded that maintaining a moist wound environment was beneficial to the wound healing. Contrary to the traditional concept that a wound should be dry to form a scab and promote healing, wet environment instead can lead to maceration and tissue breakdown to allow a wound heals faster. Based on this, sophisticated dressings providing moist, absorbent, interactive and non-toxic environments for healing was developed, but they were not suitable for all wounds and sometimes need to be monitored closely to avoid clinical infection.

2.2.3 Exudates of wounds

Based on the types of wounds and periods of healing, different wound dressings are available for the effective management of wounds [19, 47, 53]. Since this study focuses on the absorbent dressings for exuding wounds, reducing exudate levels is the main task for absorbent dressing. A balance of the degree of wet is vital to an exuding wound. A dry wound bed may cause the underlying collagen matrix and the surrounding tissue becoming desiccated, which inhibits the contraction and healing of the wound [54]. A moist wound environment is mainly sustained by exudate. The exudate mostly consists of water, but it also contains electrolytes, nutrients, proteins, inflammatory mediators, proteases such as matrix metalloproteinases (MMPs), growth factors and waste products, as well as white blood cells such as neutrophils, macrophages and platelets [19, 55, 56]. The wound exudate is produced by

vasodilation during the early inflammatory stage of healing under the influence of elevated levels of inflammatory mediators and activators such as histamine and bradykinin [3, 57-59]. However, an excessive exuding wound may prevent cell proliferation and lead to maceration and excoriation of skin [56]. Both dry wounds and wet wounds can be painful and discomfort to the patient [43]. The appropriate dressing may create an optimal wound healing environment. It helps to reduce the times of dressing changes, reduce pain and skin maceration, accelerate wound healing, be cost-effective and improve patient's life quality. The exudate management of dressing is carried out through absorbing it and/or allowing it to evaporate or some of them form a gel with the exudate. Today, advanced absorbent dressing materials include cotton, viscose or polyester textiles, polyurethane or silicone foams, alginates, hydrocolloids and Hydrogels [56, 60]. Besides traditional gauze dressings, the most popular absorbent dressings in the market, foam dressings and alginate dressings, as well as the relevant silver-containing dressings will be discussed below.

2.3 Absorbent wound dressings

Since the principles of maintaining a moist wound environment have evolved into a science, the wet environment created by great amounts of wound exudate becomes favorable to the wound healing process. Absorbent wound dressings are designed to quickly absorb exudate from the wound and retain this fluid inside their spacer zone

to offer a moist environment to the wound. Cotton gauzes, foam dressings and alginate dressings are commonly used as absorbent dressings for exuding wounds [61].

2.3.1 Wound dressing concepts

According to the moist healing process, a moist wound environment is the key factor to debridement and is obtained by using occlusive or semi-occlusive absorbent dressings [7, 62, 63]. There are a variety of methods that can be used to dress an exuding wound and keep a moist environment [64]. So the healing of a wound depends not only upon medication but also upon the use of proper dressing techniques and suitable dressing materials. The ideal characteristics of a wound dressing include [16, 17, 65]:

- Impermeability to water and bacteria;
- Freedom from particulate matter;
- Thermal insulation;
- Absorption and retention of exudate;
- Prevention of trauma on removal;
- Removal of toxic substances;
- Prevention of dehydration;
- Allowing for gaseous exchange;
- Pain relief and comfort.

Modern dressings are required to create the optimal environment for wound healing. They should be easy to apply and can reduce the nursing time with fewer dressing changes and pains of removal with less adherence between wound surface and dressing [18, 66]. A modern absorbent wound dressing normally consists of three layers, i.e., an absorbent layer, a wound contact layer and an out layer. The absorbent layer is used to absorb exudates, blood and body fluids, providing a humid environment on the wound surface. The wound contact layer with low adherence should easily be removed with less pain and less disturbing for new tissue growth. The outside layer is an adhesive diffusion layer. While fixing a wound dressing on the skin, the outer layer can provide a barrier against microorganisms, dirt and other foreign substance. A modern wound dressing model from literature is presented in Figure 2.3.

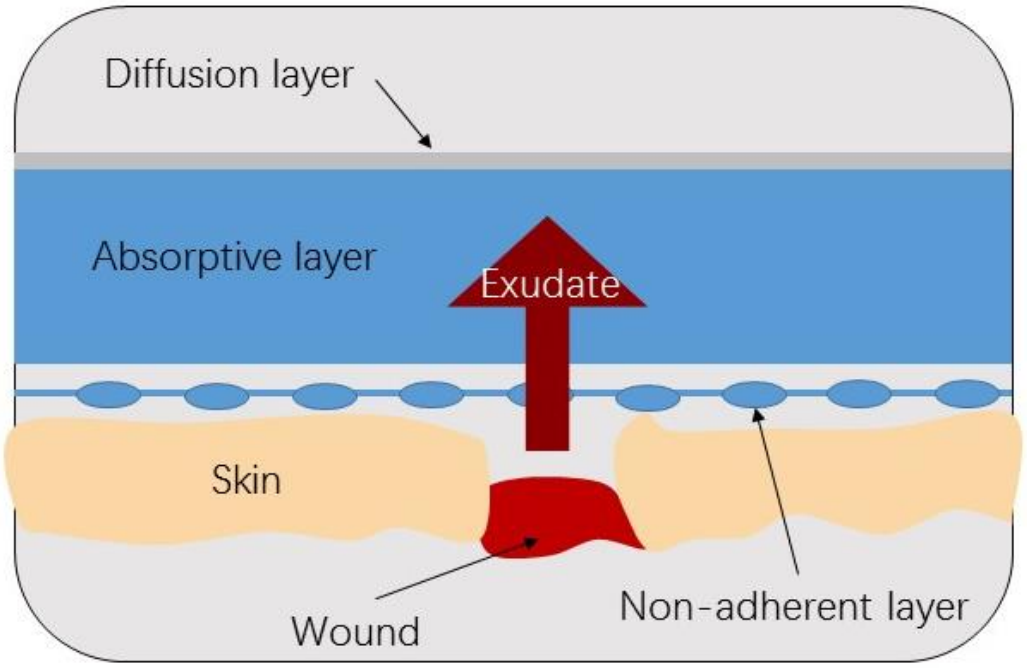


Figure 2.3 The modern wound dressing model.

2.3.2 Traditional gauze dressings

Generally, cotton gauzes are applied as dressings because they are soft, flexible and cost-effective. Gauzes are the most commonly used wound dressings today. The traditional wet-to-dry technique utilizes saline-moistened gauze, which is applied to the wound and allowed to dry. When the gauze dressing becomes dry, adhering debris and necrotic tissue can be removed from the patient and wound debridement occurs [7, 8].

A considerable number of investigations has focused on cotton gauzes treated with silver antimicrobial agents. Mohamed Gouda [67] in situ synthesized and deposited nano-silver-oxide (nano-Ag-oxide) into cotton gauze fabrics by reduction of silver nitrate solutions. The reduction rate of colony count percent (RBC) of cotton gauze fabrics containing nano–Ag-oxide against gram-positive bacteria (*S. aureus*) was 99% and gram-negative bacteria (*S. typhimurium*) was 97%, higher than those obtained with gauze fabrics containing nano-Zr-oxide. It had obvious inhibitory effect against gram-positive and gram-negative bacteria and showed no clinical signs of skin irritation.

D. V. Parikh et al. [68] developed an antimicrobial Ag/Na carboxymethyl cotton burn dressing by partial cation exchange of sodium from sodium carboxymethyl cotton gauze by silver nitrate. According to the positive antimicrobial evaluation results, the

dressings containing the silver antimicrobial agent could protect wound surfaces from microbial invasion and effectively suppress bacterial proliferation. The increased retention of silver nitrate solution on the dressing lessened replenishment of solution, which would reduce nursing time.

A simple one-step synthetic route was used to prepare silver nanoparticles by reduction of silver nitrate on cotton gauze [69]. The test result showed that the cotton gauze with silver nanoparticles inhibited different Candida strains and its antimicrobial activity was high. However, cotton gauze allows moisture to evaporate from the wound surface. Thus, gauzes tend to be dry rather than maintaining the moist environment to facilitate wound healing. In addition, cotton gauze is easy to adhere to the wound and requires frequent changes, causing trauma and pain to the patients [9].

2.3.3 Foam dressings

Foam dressings are generally made from polyurethane foam [10]. While all the foam dressings are hydrophilic, their absorbent rates and absorbency vary with composite and thickness. Fast absorbent rates can accelerate vertical wicking and keep exudate off the wound to decrease maceration. Good absorbency may allow the patients to change dressings less frequently. Some foam dressings provide absorption capacity up to 7 days [70]. A range of shapes and sizes are available for relieving the pressure of

challenging areas (Figure 2.4). Foam dressings are mainly applied to heavily exuding wounds, especially during the inflammatory phase following debridement and sloughing, when drainage is at its peak [71]. They are also recommended for deep cavity wounds to prevent premature closure as they can maintain a moist environment by absorbing exudate. Foams can be applied in weeping ulcers, such as venous stasis, but not recommended for dry superficial wounds.

Figure 2.4 Foam wound dressings with different size and shape on the market.

Foams may be impregnated or layered in combination with silver to improve their antibacterial performance and to promote wound healing process. A specialized antimicrobial silver foam dressing S-ROCF was evaluated *in vitro* for efficacy against Staphylococcus aureus and Pseudomonas aeruginosa pathogens. The antimicrobial testing result showed a 99.99% reduction in colony forming units, and continuously effective after 72 h of simulated V.A.C. Therapy. The antimicrobial and mechanical characteristics of the aged foam were found to be as good as the unaged foam through an accelerated aging process [72].

Bo Jørgensen et al. [73] discovered that the silver-releasing dressing, Contreet Foam, provided superior performance than traditional moist foam wound healing dressing, Allevyn Hydrocellular, in the treatment of chronic venous leg ulcers. There was a significantly greater reduction in ulcer area, less odor and fewer leakages in the Contreet Foam group than in the Allevyn Hydrocellular group.

It was suggested that the silver-releasing foam dressing brought a great amount of benefits in the treatment of wounds. Their good absorbency reduced leakage and maceration to surrounding tissue, suggesting good exudate management capabilities. The antimicrobial performance of silver foams contributed to the healing process and the decrease of infection. They could also cut down the wound malodor by reducing maceration and infection. Currently, there are many silver foam dressings on the market, such as Allevyn Ag from Smith & Nephew, Mepilex® Ag with Safetac® technology from Mölnlycke Health Care, Biatain Ag Non-Adhesive or adhesive with a patented silver complex from Coloplast. Although silver foam dressings can solve tough problems during the exuding stage of the healing process, the price of commercial foam dressing is very expensive, usually dozens of times higher than normal cotton gauze, which limits the utilization of foam dressings [11], especially in developing areas.

2.3.4 Alginate dressings

Alginate wound dressings are made of soft non-woven fibers derived from brown seaweed. When placed within the wound bed, alginate dressings react with serum and exudate by exchanging sodium ions with calcium ions that are exuded from the wound. The exchange in ions creates a fibrous gel, providing a moist and warm wound environment [74] and preventing dressing fibers from contaminating the wound as the gel is easy removal [75]. Three forms are available for alginate wound dressings (Figure 2.5). Alginate sheets may be placed on wound beds to absorb drained exudate. A collagen-alginate wound dressing is also an effective dressing for the management of foot ulcer [14]. A calcic-sodium alginate dressing was utilized as an effective dressing in the treatment of pressure ulcers, bleeding and/or infected vascular ulcers [76]. Alginate ropes are effective and easy to use for the treatment of cavity wounds by tightly filling wound tunnels or areas of undermining [77]. Alginate-tipped applicators can be used to probe wounds. Different from foams, alginate dressings have also been applied to donor site healing due to consistently better healing under the calcium alginate [59, 78, 79].

Figure 2.5 Alginate wound dressings on the market.

However, a majority of alginate dressings may trap bacteria, which often gives rise to wound malodor and brings unpleasant experience to patients. Silver-containing alginate dressings can reduce bacteria to a certain degree. Yimin Qin [80] developed a silver-containing alginate dressing through first mixing a silver sodium hydrogen zirconium phosphate Alphasan RC5000 with sodium alginate solution, then suspending fine particles uniformly under a high rate of shearing, finally spinning fibers and forming non-woven alginate dressing. The result showed that these silver-containing alginates are highly effective against bacteria. C. Trial et al. [81] compared the efficacy and tolerability of the silver alginate matrix, Askina Calgitrol Ag with those of a standard silver-free alginate dressing, Algosteril. They were similar in the regression of local signs of infection, tolerance, acceptability and usefulness. However, Askina Calgitrol Ag improved the bacteriological status of the wounds. Steven L Percival et al. [82] demonstrated the broad antimicrobial activity of a silver alginate dressing on wound isolates grown in the non-biofilm and biofilm state. It was found that the silver alginate dressing was able to inhibit the growth of all microorganisms

tested, including strains of Candida albicans, meticillin-resistant Staphylococcus aureus, S. aureus, vancomycin-resistant Enterococci, Enterococcus faecium, staphylococci and viridans streptococcus.

Alginates are highly permeable and non-occlusive, and therefore, they require a secondary dressing, most commonly gauze [14, 76, 83]. Except the combination with gauzes, alginate dressings have been used with carboxymethyl cellulose, showing a statistically significant improvement in healing [84]. The key point to solve the non-occlusive problem of alginates is to maintain the moist wound environment after absorbing several times mass of fluid.

2.3.5 Limitations

As mentioned above, the main limitations of the currently available dressings for heavy exudate wounds can be summarized as follows [3, 17, 19-21]:

(i) The majority of high absorbent dressings are made of foams, alginate, hydrogel, hydrocolloid, etc., and cannot retain their original shape or integrity during the use. Therefore, cleaning or washing to remove the remnants of such dressings left in the wound is required [85];

(ii) Wound malodor is partially caused by heat generation from skins and poor air permeability;

(iii) Low extensibility reduces the comfort when applied to a joint or a region of movement of the body;

(iv) Limited shapes and sizes lead to dressing fit less compactly;

(v) Some of them are adherent to the wound, causing trauma and pain on removal;

(vi) The costs involved are high.

2.4 Three-dimensional spacer fabrics

Three-dimensional spacer fabrics consist of sandwich structures, which have two separate outer layers connected by spacer yarns in the middle [22, 23]. These fabrics can be produced by weaving, nonwoven, warp knitting or weft knitting technologies [86]. As weft-knitting method is easily controlled, the spacer fabrics were produced on weft-knitting machine in this study.

2.4.1 Fabrication of spacer fabrics

Weft-knitted spacer fabrics are manufactured with either flat (Figure 2.6 (a)) or circular (Figure 2.6 (b)) weft knitting machines with two needle beds. For the spacer fabrics knitted on the flat knitting machine as shown in Figure 2.6 (c), the two surface layers on the front and back needle beds are separately knitted, and then connected by the tuck loops between the two needle beds which forms the spacer layer. The distance

between the two needle beds of flat knitting machines is fixed, which mainly determines the thickness of the spacer fabrics. The thickness is also affected by the tuck structures (Figure 2.7) and steaming process. The steaming process makes spacer fabrics shrink in both course and warp directions, and the steaming temperature and time may affect the shrinkage. The needle connecting distance, inclination of spacer yarns and the elasticity of surface yarns also influence the shrinkage [87], thus influence the thickness of spacer fabrics. The major difference of circular knitting machine comparing with flat knitting machine is that the distance between the two sets of needles can be adjusted by varying the dial height relative to the machine cylinder. In this way, the spacer fabric thickness can be adjusted [86].

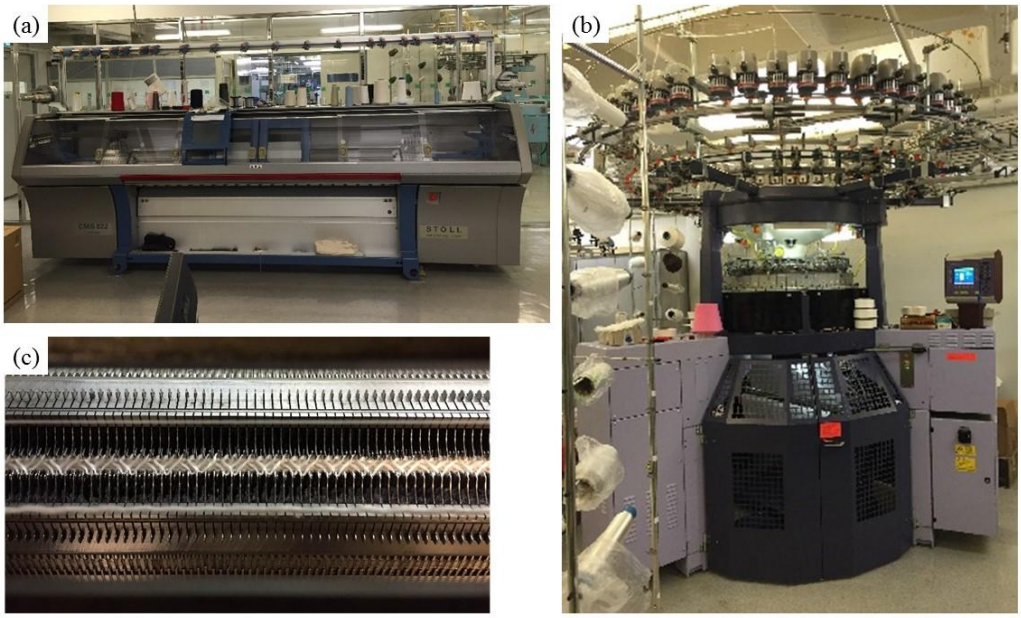


Figure 2.6 (a) A STOLL computerized flat knitting machine; (b) a Terrot double jersey circular machine; (c) knitting a spacer fabric on the computerized flat machine.

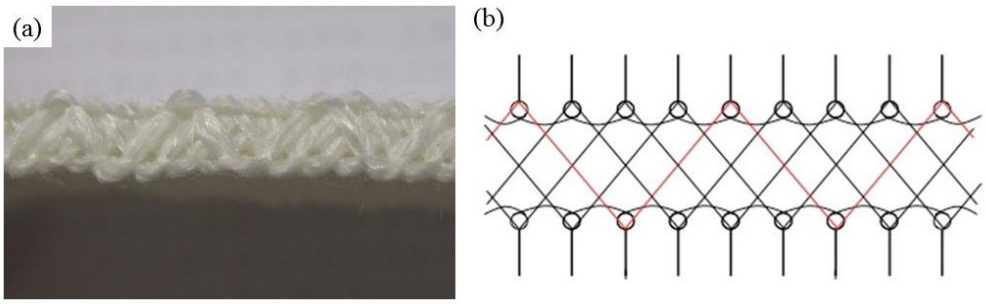


Figure 2.7 Tuck structure of a typical weft-knitted spacer fabric produced with flat knitting machine: (a) real fabric, (b) scheme.

The productivity of weft-knitted spacer fabrics is relatively low, because of their tuck knitting mechanism. However, weft-knitting is easily controlled by simply changing knitting parameters. There is no need to prepare numbers of warp beams and spun yarns like warp knitting, which makes the operation very convenient. These are the reasons for choosing weft-knitted spacer fabrics in this study.

2.4.2 Properties and applications

The 3D nature of spacer fabric structure imparts them unique properties [24]. These properties play important roles in improving the wearing comfort and protection while using as apparels or medical care. Numerous research works have recently demonstrated promising applications of spacer fabrics as protective devices, compression bandages and incontinence pads [88-91].

The mechanical properties of spacer fabrics are outstanding. Spacer fabrics can be used as cushioning materials for pressure relief because they absorb kinetic mechanical energy under compression [92]. The cushioning behavior of spacer fabrics can be similar with the widely-used cushioning polyurethane foams whereas the air permeability and moisture transmission property of spacer fabrics are much better than foams [23]. Spacer fabrics are also applied in vibration isolation systems due to their negative stiffness [87]. The comfort of spacer fabrics is good when the fabrics are used as human vibration isolators [70]. The spacer fabrics with cushioning effects and vibration isolation were applied in car seats [93, 94], wheelchair cushions and sports protector such as knee braces [95].

Spacer fabrics are breathable with high air permeability due to the mesh structures in outer layers and porous structures in the spacer layers [86]. The NP values and tuck connecting distances affect the air permeability of spacer fabrics [22]. Spacer fabrics can also be used as a sound absorber as porous materials are often used as passive mediums for sound absorption [96]. Good sound absorbability could be achieved by adjusting knitting structures and parameters of spacer fabrics [97]. Spacer fabrics can generate thermal comfort and regulate human body temperature when fabricated with different types of yarns on different layers [98]. The thermal conductivity is closely related to the spacer fabric density [99].

It has been shown that spacer fabrics have good moisture management and wicking property. R. Bagherzadeh[100] et al. found that sweat transferring ability of spacer fabric can be significantly improved by using the profiled cross section fibers, like Coolmax fiber. Sedigheh Borhani [101] et al.'s findings on moisture transfer of spacer fabrics showed that water vapor could be easily and quickly transferred from close to the skin to the outer surface of spacer fabric to keep the skin dry.

Spacer fabrics can have high water absorbency and be used as absorbent dressings. Angela Davies [27] et al. investigated the use of spacer fabrics for absorbent medical applications. They tested the absorbency and liquid spreading inside spacer fabrics and found that spacer fabric containing roving in the central spacer zone had the best absorbency and control over the area of spreading. Spacer fabrics were patented as an incontinence product to absorb a large amount of liquid [102]. Tilak Dias [103] et al. found that knitted structures with high porosity absorb more water than those with low porosity. Shuk-fan Tong [28] et al. recently reported that warp-knitted spacer fabrics could be used as a substitute of the absorbent layer for advanced wound dressing. Their study confirmed the good air and water vapor permeability of spacer fabrics. However, the fabrics used in their study were just collected from the market. Until now, spacer fabrics particularly designed and fabricated for wound dressing with high liquid absorption and retaining are still needed.

Spacer fabrics can well overcome the above-mentioned drawbacks and can maximize their performance as dressing material. Spacer fabrics are breathable with high air permeability, which is important to odor removal. They have good ability to control heat and moisture transfer, keeping moist and thermal insulating environment for wound healing. Spacer fabrics are soft, having good resilience that can provide a good cushioning effect to the body [25]. Spacer fabrics also guarantee a good distribution of pressure and good press elastic behavior [26], so that the wound could be protected from physical and mechanical movements. These solid textiles are lightweight and can provide support to the body against injuries [104]. Because of their integrity and tear resistance, spacer fabrics maintain the original shape for a long time. In addition, required shapes and sizes to be conformable with body areas are accessible by different knitting technology [105-107]. An important advantage of spacer fabrics is that the knitted structures can be adjusted according to different requirements of absorbency and water vapor permeability, to adapt to different types and stages of exuding wounds. These changes on spacer fabrics can be easily and cost-effectively realized through rearranging the spacer yarn connecting distance, number of elastic yarns and type of spacer yarn or other structure factors. The comprehensive properties of spacer fabrics make them suitable for applying as absorbent dressings for exuding wounds. This application can well overcome the drawbacks of current absorbent dressings.

2.5 Water resistant treatment

As mentioned above, spacer fabric could provide a moist environment to accelerate wound healing and offer good permeability to avoid malodor and maceration, which benefit from the three-dimensional structure of spacer fabric. However, a wound dressing which performs like skin should also prevent contaminated fluid and harmful substance accessing the wound. The protective function against water and other fluids is required. Making the outer layer of a dressing to be water resistant can meet this requirement. Although waterproof products have been surveyed for many years, a great amount of them, especially waterproof coatings, are non-permeable or have very low air and water vapor transmission [108]. In this study, water resistant treatments with good air permeability were investigated.

2.5.1 Treatment with electrospun nanofibrous membrane

It is found that electrospun nanofibrous membrane can be highly permeable due to their special fibrous structures. The pore sizes of non-woven nanofibrous membrane mats were reported from 500 nm to 1 μm [109]. So electrospinning has the ability to introduce porous surface with high air permeability. According to the literature [109], more than 15 different polymers have been successfully applied in electrospinning to form nanofibers. Most of them were dissolved in solvents while using, and a few of them were molten in high temperature which required vacuum condition.

Among the spinnable polymers, polystyrene and polyurethane were suitable for nanofiber formation. What is more important, the nanofibrous membranes made of these two kinds of polymers were often reported water resistance. The polystyrene nanofibrous materials have been found superhydrophobic [110]. It can be a substitute for fluorochemical water resistant agents. Numbers of research works related to electrospinning of polystyrene have been conducted. Zheng [111] et al. found that water contact values of electrospinning polystyrene surfaces were in the range of 140°-160°, varying with the structure of fibers. Kang [110] et al. prepared electrospun fibers from polystyrene solutions with several solvents, including THF, chloroform and DMF, and the water contact angle of the polystyrene film reached 152°. Lin [112] et al. investigated the fabrication of polystyrene fibers via electrospinning, revealing the effects of solvent compositions and polymer concentrations on electrospinning.

Polyurethane nanofibrous materials are also water resistant. The polyurethane coated permeable textile was generated in the literature [113], and the waterproof was higher than 10,000 mm H_2O and the water vapor permeability was higher than 900 g/(m^2 × 24 h). The effects of concentration and instrument parameters on the morphology and diameter of polyurethane electrospinning were investigated in detail [114]. As polyurethane foams have often been used as wound dressings, polyurethane is a kind of medical material without toxicity. Water resistant surfaces with high water contact angles can be produced using polyurethane and polystyrene. In addition, the

electrospinning processes of polyurethane and polystyrene were investigated in numbers of previous studies. In this study, we mainly focused on the properties of designed wound dressings, instead of the electrospinning processes of polyurethane and polystyrene. Therefore, polyurethane and polystyrene electrospun nanofibrous membranes were selected for covering the surfaces of wound dressings to prevent wounds from contaminated fluids.

2.5.2 Treatment with fluorochemicals

Fluorochemicals were one of the most commonly used water repellent agents in textile finishing. Waxes, oils and silicones are also applied as water repellent agents, but these compounds can be penetrated by oil. Fluorocarbons are the most effective at repelling both oil and water. Fluorine has the highest electronegativity among all the elements. The bond energy of C-F (116 kcal/mol) is 16.5 kcal/mol higher than C-H (99.6 kcal/mol). Besides, the covalent radius of fluorine is small, around 60 picometers [115]. The polarizability of fluorine of C-F bond is very small [116]. Therefore, the intermolecular cohesion in compounds with numbers of C-F bones is low, and the surface energy of the compounds is low. Surfaces made of these compounds can hardly be wetted or contaminated [117]. Generally, surfactants can lower the surface tension of water to 30 dyn/cm. Fluorochemicals can reduce the surface tension of water to 10 - 15 dyn/cm. Also, the surface tension of oils considerably decreases when

fluorochemicals added. It is noticeable that superhydrophobic surface can be obtained using fluorocarbon solution of low concentration. The textiles finished with fluorocarbons are air permeable and soft.

Both fluoropolymers and fluorine-containing monomers have been used as textile finishing agents, which generally consist of 4 parts in their chemical structures [118-120]. The most important part is the fluorocarbon compound, which introduces resistance to water, oil and dirt. Another part is stable chain to balance the high polarity of C-F bond, such as - $(-CH_2-)_n$ -, $-SO_2NH-$ and so on. The third part is an unsaturated chain for polymerization, including acrylic acid, ethylene and styrene. The fourth part is functional groups which bring particular properties to textiles. For example, silicon-containing compounds could improve fabric softness and handle.

The issue deserves careful attention is the pollution and toxicity of fluorochemicals. There are potential safety and health concerns with two fluorochemicals: perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) (trace impurities of C8 chemistry). Although their toxicokinetics is different, both chemicals are likely carcinogenic in rodents [121]. Because PFOS and PFOA are hydrophobic and lipophobic, they are not accumulated in lipids of organisms, whereas they tend to adhere to proteins, so the PFOS and PFOA concentration of protein-rich tissues such as liver, kidney and blood are high [122-126]. In addition to the health problem, the

persistence of PFOS and PFOA in the environment makes them restricted by the European Union and US environmental departments. Both chemicals can hardly break down, and levels of these chemicals accumulating in the global environment are increasing. Alternatives to PFOS and PFOA for textile water repellent finishing are required.

Since superhidrophobic and lipophobic surfaces are hardly achieved by current non-fluorinated agents, other fluorocarbons with different structures have been investigated as alternatives to PFOS and PFOA. The bioconcentration and bioaccumulation of perfluorinated acids were reported directly related to the length of compound's fluorinated carbon chain [124]. Nowadays perfluorinated substances with a shorter chain length (C6 and C4) repellents with less hazardous properties can substitute C8 repellents which might contain traces of PFOA [127]. The majority of current durable water repellent (DWR) products are treated with C6 repellents [128]. C6 fluorocarbon-based repellents are PFOS-free, but PFOA is still detectable on the treated fabric at a very small amount around 100 ppb (parts per billion) [129]. According to the bluesign® criteria [130], C6 repellents have no DNA damage, genotoxicity and reproductive toxicant. They can be rapidly bioeliminated, which means they are not bioaccumulative and dose not persist in our living environment.

Nuva N is a sustainable C6-based fluorocarbon repellent developed by Clariant [131]. It is free from PFOA and their repellent performance is comparable to the traditional C8 products. The simple finishing process of Nuva N can impart long-lasting soil repellency to fabrics, while being compatible with other finishing chemicals [132]. Conventional fluorocarbon treatments usually harden the fibers, thus, the fabric handle is stiff like paper. The abrasion and tear strength of fabrics are also affected by the repellent processes. Nuva N repellent, however, imparts a softer hand to fabrics having a positive impact on tear strength and abrasion resistance [133]. In this study, the fluorocarbon agent Nuva N2114 was applied as the water repellent.

2.5.3 Treatment with TiO_2 nanosol

As a kind of fluoride-free repellent, inorganic nanoparticles including TiO_2, SiO_2 and ZnO have been usually used in superhydrophobic treatments to form self-cleaning surfaces. These inorganic nanoparticles have very high specific areas, which can considerably reduce the surface energy and increase surface roughness like the repellent lotus/rice leaves or bird feathers in nature. Numbers of works involving the surface properties of TiO_2 have been carried out. A robust superamphiphobic film made from electrospun TiO_2 nanostructures was obtained, and its surface contact angle of water and hexadecane was 166° and 138.5°, respectively. The contact angle hysteresis for water and hexadecane was 2° and 12°, respectively [134]. Lai et al. [135]

fabricated superhydrophobic spongelike nanostructured TiO_2 surfaces. Surfaces with very good superamphiphobic effects could be formed using TiO_2 nanoparticles. Photocatalytic wettability conversion of superhydrophobic TiO_2 surfaces could be realized because of the unique UV-stimulated wettability conversion property of TiO_2 [136-138]. TiO_2 nanoparticles are often used in textile finishing. Except self-cleaning [139, 140] and hydrophobicity, UV-protection [141-144], antibacterial effects [145-147] can also be obtained by treating fabrics or fibers with TiO_2 nanostructures. Since wound dressings directly contact with skins and wounds, fluoride-free products are considered safer for the surface treatment of spacer fabrics. The special properties of TiO_2 nanostructures attributed to the selection of TiO_2 nanosol as a water repellent in this study. The UV-protection and antibacterial effects could be positive to the medical application of spacer fabrics.

2.6 Conclusion

This chapter has reviewed the literature related to this study, including wounds and wound healing process, absorbent wound dressings and three-dimensional spacer fabrics and water resistant treatment. Different types of wounds and the four phases of wound healing process have been reviewed. The moist wound healing principle has been studied for years, which proved that a moist environment was helpful for wound. Especially, the effects of exudates for wound healing have been discussed. Based on

this, the requirements of exuding wound care have been illustrated. An ideal dressing should provide a moist environment on the wound surface, and at the same time can provide a barrier against microorganisms, dirt, and other foreign bodies. In addition, it can remove exudate and be removed without disturbing new tissue growth.

A modern wound dressing applied to exuding wounds normally consists of three layers, namely, a wound contact layer, an absorbent layer, and a barrier surface layer, where the absorbent layer is sandwiched between the other two layers. However, current commercial dressings for heavy exudate wounds still have some drawbacks, such as poor integrity, wound malodor caused by poor air permeability, skin maceration because of low water vapor transmission, and high prices. The previous studies on spacer fabrics have shown that such fabrics are capable of absorbing exudate and possible to control moisture. Spacer fabrics can well overcome the drawbacks of currently absorbent wound dressings. The use of spacer fabrics as exuding wound dressing is a potential way to introduce better wound care conditions.

Chapter 3 Design and fabrication of spacer-fabric-based dressing

3.1 Introduction

The purpose of this study is to develop a novel absorbent dressing based on spacer fabric with ideal dressing properties to promote the wound healing. As reviewed in Chapter 2, the requirements of an ideal dressing include high absorbency, good permeability of vapor and air, antimicrobial and biocompatibility. The dressing for exuding wound should be designed according to these requirements. Meanwhile, the fabrication methods and the properties of spacer fabric should also be considered.

Firstly, the structure of the designed spacer-fabric-based dressing for exuding wound is illustrated. Each layer of this structure has its own function, such as water resistant or absorbent, so the production methods and materials used for each layer should be formulated differently. For the overall dressing, it is required to be air permeable and water vapor transmittable, therefore, the considerations to keep the spacer-fabric-based dressing permeable for air and water vapor are also needed when design the dressing.

Then, the fabrication and selection of suitable spacer fabrics are presented. According to the design, the yarns of surface layers should be hydrophobic, so polyester/spandex yarns were selected. The yarns of middle layer should be absorbent, so cotton and Tencel yarns were used. Different knitting structures were also fabricated and evaluated according to their wettability, absorbency, air permeability, water vaper permeability and thermal property. Statistical analysis was carried out to select the optimal material and structure for wound dressing.

3.2 Design of spacer-fabric-based dressing

It is well known that a modern absorbent dressing normally consists of three layers (a wound contact layer, an absorbent layer, and an outer layer) and each layer should have different functions. For the wound contact layer, a hydrophobic surface is beneficial to moisture transmission from the wound bed to the absorbent layer in order to avoid pre-skin maceration. For the outer layer, it should be waterproof to protect the wound from contaminated fluids and risk of infection. For the absorbent layer, its main task is to quickly absorb exudate and retain exudate for a long time to create a moist wound environment. According to these requirements, the fundamental structure of the dressing to be designed should have two hydrophobic layers containing an absorbent layer. In addition, the whole dressing structure should have good air

permeability and water vapor transmission as well as antimicrobial property and biocompatibility.

To achieve these requirements, a multi-functional dressing was designed based on three-layered spacer fabric structure. As shown in Figure 3.1, the spacer fabric was the base material of the designed dressing structure. Its two surfaces were produced with elastic synthetic fibers to make them hydrophobic, extensible and conformable. Thus, the wound contact layers of the dressing were hydrophobic. The middle layer of the spacer fabric was used as the absorbent layer. It was knitted with absorbent yarns having good absorbency and moisture conductivity. The wetting speed and amount of absorbed fluid can be controlled by using different types of absorbent yarns. Due to the nature of porous textile structure, water vapor and air could easily pass through the whole dressing structure. The stitch density, which has great effects on absorption, permeability and comfort, could be adjusted by changing the knitting parameters. The appropriate thickness and areal mass of the dressing could be obtained through adjusting spacer yarn length and size of surface yarns.

To avoid bacteria being trapped in the dressing, the spacer fabric was treated with antibacterial agents by a simply pad-to-dry process. To enhance the waterproof property of the outer layer of dressing, at the same time to not affect its permeability, a permeable membrane was further added to cover the outer layer of spacer fabric after

the spacer fabric had been knitted. The permeable membrane could be a nonwoven structure which was formed via an electrospinning process by spraying nanofibers on the spacer fabric outer surface or a coating layer which was formed via spraying coating with waterproof agents. The materials and chemical agents used in the dressing production should be biocompatible to avoid cytotoxicity and irritation.

Based on this design, a spacer-fabric-based dressing with good absorbency, permeability, waterproof and antibacterial property could be realized by the proper usage of yarns, knitting parameters and functional finishing. The designed dressing could provide a moist and germ-free environment to wound and promote wound healing.

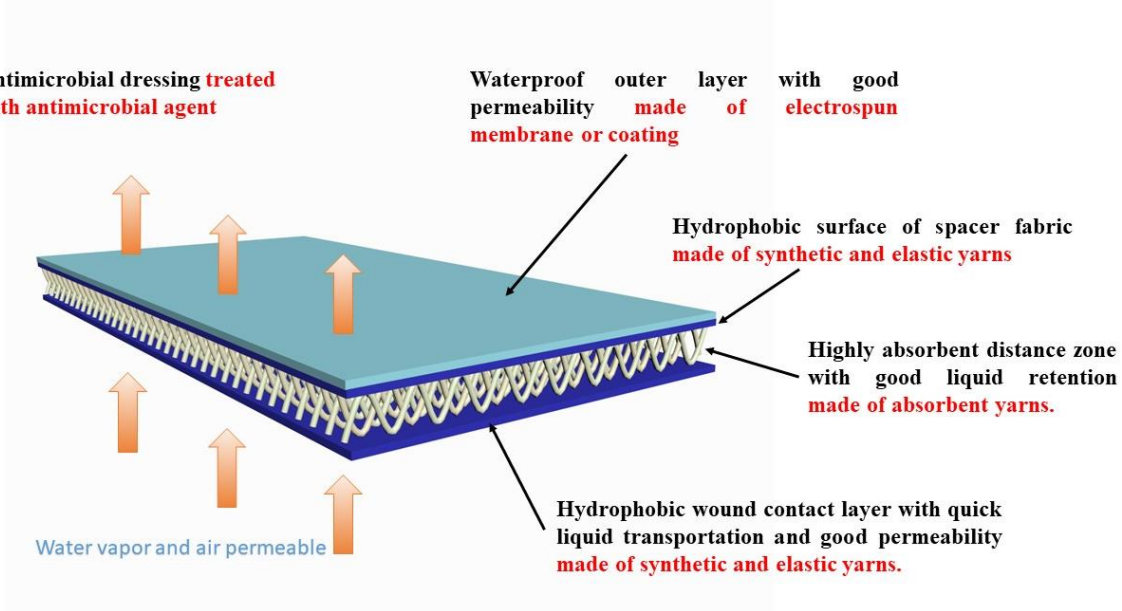


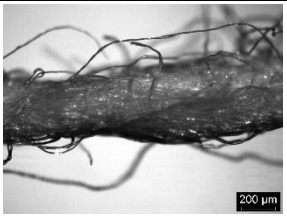
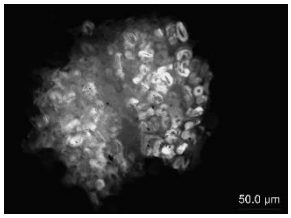
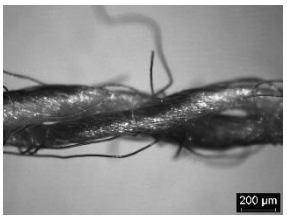
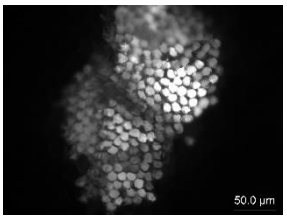
Figure 3.1 Wound dressing designed based on spacer fabric structure.

3.3 Fabrication of spacer fabrics

Spacer fabric structure was the backbone and base material of the designed dressing. Two fabrication processes, knitting and steaming, were carried out to obtain the designed fabrics. Spacer fabrics were first knitted with a 14-gauge STOLL CMS 822 computerized flat knitting machine due to the simpler fabrication process and easy knitting parameter control as well as the easy use of elastic and spun yarns. The outer single jersey layers were knitted with single or double polyester/spandex (100D/40D) yarns provided by Tailin (Zibo, China) Textile Co., Ltd. The moisture regains of all the yarns were tested according to standard ASTM D2495. The moisture regain of the polyester/spandex yarns was 1.0%. The spacer layer (distance zone) was knitted with different spacer yarn lengths (different spacer yarn connecting distances as shown in Figure 3.2) using 32S/2 bleached cotton or Tencel yarns provided by Meikesi (Dongguan, China) Yarn Co., Ltd. The reasons for selecting cotton and Tencel yarns as the spacer yarns was their good absorbency and low cost. Although cellulosic fibers are considered to grow bacterial in the wet condition, antibacterial treatments can be carried out to solve this problem. Antibacterial treatments on cotton and Tencel spacer yarns will be conducted to produce a reliable wound dressing in the next step. As the spacer yarns play the main role in the performance of spacer fabrics, their morphologies and properties are specially given in Table 3.1. The linear density of yarns was tested according to standard ASTM D3818. The breaking strength and elongation were tested on Instron 1144 tensile tester according to standard ASTM

D5034. The yarns were conditioned in the standard atmosphere, so their moisture regains were similar to the conventional moisture regains. The images of surface and cross section of yarns were taken using Nikon OPTIPHOT-POL microscope.

Table 3.1 Morphologies and properties of spacer yarns used.

	Linear density (tex)	Breaking force (cN)	Breaking elongation (%)	Moisture regain measured (%)	Images of yarns
Cotton yarn	39.72 (± 1.75)	539.7 (± 11.8)	7.95 (± 0.37)	8.5 (± 0.399)	 Surface  Cross section
Tencel yarn	35.71 (± 1.01)	746.6 (± 16.3)	8.90 (± 0.33)	11.3 (± 0.884)	 Surface  Cross section

Note: Standard deviations are given in parentheses.

After knitting, all spacer fabrics were subjected to a steaming treatment to allow shrinkage of the surface layers without damage of spandex yarn. The steaming treatment was carried out at around 98 ºC for 30s using an HSL-611 steam iron produced by NAOMOTO Corporation, Japan. After the steaming treatment, the fabric samples were conditioned at 20 ºC and 65% RH for a week to release their internal stress. After full relaxation, the spacer fabrics with stable dimensions were obtained for further test. The 3D view of a typically fabricated spacer fabric is shown in Figure 3.3.

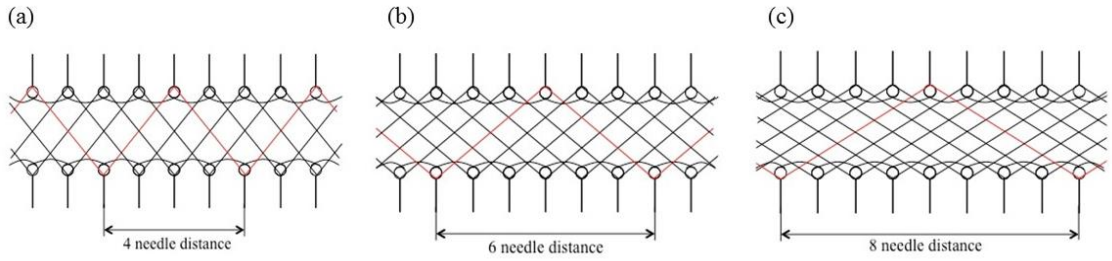


Figure 3.2 Spacer fabric structures with (a) 4, (b) 6, (c) 8 needle connecting distance.

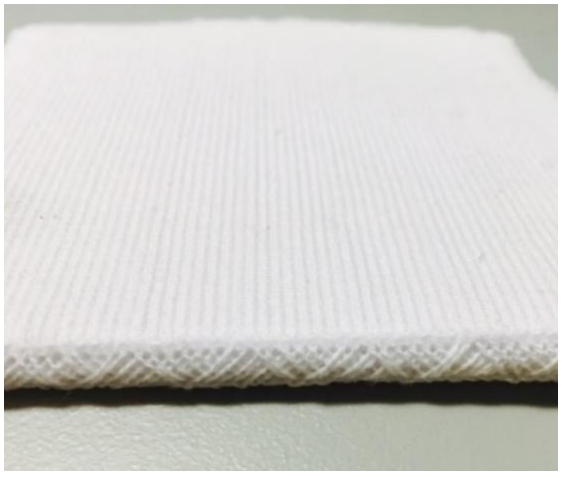


Figure 3.3 3D view of a typically fabricated spacer fabric.

Table 3.2 Details of produced spacer fabrics.

Fabric code	C4-1	C6-1	C8-1	C4-2	C6-2	C8-2	T4-1	T6-1	T8-1	T4-2	T6-2	T8-2
Type of spacer yarns	Cotton	Cotton	Cotton	Cotton	Cotton	Cotton	Tencel	Tencel	Tencel	Tencel	Tencel	Tencel
Number of surface yarns	1	1	1	2	2	2	1	1	1	2	2	2
Spacer yarn connecting distance	4	6	8	4	6	8	4	6	8	4	6	8
Surface stitch density: Stitch density (loops/cm^2)	112.0 (± 11.90)	113.6 (± 9.503)	116.6 (± 10.29)	132.8 (± 4.382)	131.2 (± 4.382)	118.5 (± 6.576)	145.5 (± 4.108)	144.1 (± 4.798)	140.6 (± 4.669)	140.0 (± 8.063)	132.0 (± 5.657)	126.4 (± 3.578)
Surface stitch density: Wale direction (courses/cm)	13.0 (± 0.707)	13.2 (± 0.447)	14.2 (± 0.447)	16.4 (± 0.548)	16.4 (± 0.548)	15.8 (± 0.447)	15.0 (± 0.001)	16.2 (± 0.274)	15.8 (± 0.447)	15.9 (±0.224)	15.9 (± 0.224)	16.0 (± 0.001)
Surface stitch density: Course direction (wales/cm)	8.6 (± 0.548)	8.6 (± 0.548)	8.2 (± 0.447)	8.1 (± 0.224)	8.0 (± 0.001)	7.5 (± 0.354)	9.7 (± 0.274)	8.9 (± 0.418)	8.9 (± 0.224)	8.8 (± 0.447)	8.3 (± 0.274)	7.9 (± 0.224)
Porosity (%)	89.0 (± 0.5)	87.9 (± 1.0)	88.0 (± 0.6)	85.9 (± 0.7)	85.4 (± 0.6)	85.5 (± 0.3)	87.5 (± 0.4)	87.1 (± 0.4)	86.7 (± 1.00)	86.1 (± 0.6)	85.7 (± 0.5)	86.0 (± 0.9)
Areal mass of spacer yarns (g/m^2)	435.6 (± 11.43)	578.2 (± 14.76)	770.2 (± 21.79)	488.2 (± 10.84)	615.8 (± 19.24)	743.8 (± 23.71)	484.8 (± 13.28)	648.2 (± 19.11)	779.7 (± 27.40)	499.8 (± 11.93)	652.0 (± 19.34)	718.1 (± 18.52)
Areal mass of fabric (g/m^2)	540.4 (± 21.36)	684.7 (± 20.14)	885.6 (± 17.84)	712.2 (± 16.27)	837.2 (± 12.13)	923.3 (± 29.44)	616.4 (± 16.55)	773.4 (± 21.06)	899.0 (± 21.33)	738.3 (± 10.89)	873.1 (± 24.88)	941.0 (± 32.10)
Fabric thickness (mm)	3.253 (± 0.093)	3.736 (± 0.064)	4.860 (± 0.220)	3.388 (± 0.178)	3.820 (± 0.035)	4.548 (± 0.112)	3.343 (± 0.070)	4.052 (± 0.074)	4.547 (± 0.152)	3.387 (± 0.023)	4.168 (± 0.114)	4.553 (± 0.157)

Note: Standard deviations are given in parentheses.

By combining two numbers of surface yarns, three spacer yarn connecting distances and two kinds of spacer yarns, 12 different fabrics were produced. In order to facilitate the identification of fabrics, each kind of fabric is designated with three codes as listed in Table 3.2. The first code is used to indicate the type of fiber used for the spacer (absorbent) layer. C means cotton and T means Tencel. The second code is used to indicate the connecting needle distance of spacer yarns. The third code is used to indicate the number of yarn used for the surface layers. The cross-section pictures of all twelve spacer fabrics are presented in Figure 3.4. These fabrics having different areal mass, thickness, surface stitch density, mass of spacer yarns and porosity, are also shown in Table 3.2. The spacer fabrics were made of spacer yarns and surface yarns. The density of fibers of spacer fabric could be calculated using Equation 3.1.

$$\rho\ (g/cm^3) = \rho_1 \times W_1/W + \rho_2 \times W_2/W \qquad \text{Equation 3.1}$$

ρ_1 is the density of spacer yarn (g/cm^3) , ρ_2 is the density of surface yarn (g/cm^3), W_1 is the mass of spacer yarn (g), W_2 is the mass of surface yarn (g) and W is the mass of whole fabric (g).

So the porosity of samples was determined according to Equation 3.2.

$$\text{Porosity}\ (\%) = (V_m - V_p)/V_m \times 100 = (1 - (W_m/\rho)/V_m) \times 100 \qquad \text{Equation 3.2}$$

V_m is the total volume of fabric(cm^3), V_p the actual volume of fibers (cm^3), ρ is the density of fibers (g/cm^3) and Wm is the mass of fabric (g).

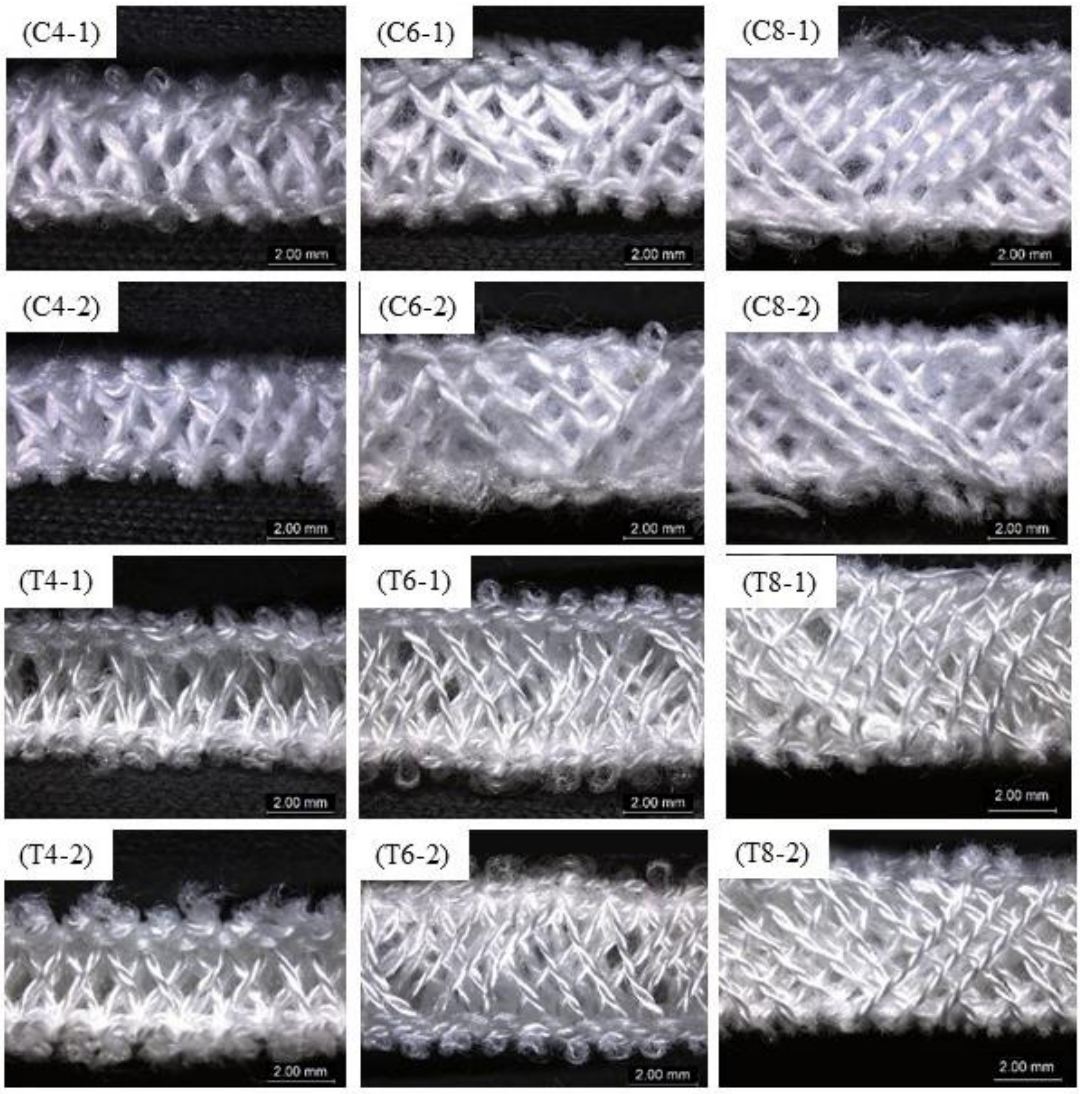


Figure 3.4 Cross-section of spacer fabrics.

From Table 3.2, it can be found that the spacer fabrics knitted with two polyester/spandex yarns for their surfaces and longer spacer yarn connecting distance

have a higher thickness and areal mass, as well as higher areal mass of spacer yarns and smaller porosity. This phenomenon is partially caused by the shrinkage of spandex yarns, which happened in the steaming process (Figure 3.5). When elastic spandex yarns shrinking, the distance of spacer zone was enlarged (h_1<h_2) and the inclination angle of spacer yarn increased (α_1<α_2) and the density of fabric increased. The more the number of polyester/spandex, the larger is the shrinkage. The larger shrinkage of spacer fabrics with two polyester/spandex yarns led to the larger thickness and area mass. Within the same number of needle connecting distance for spacer yarn, the spacer fabrics knitted with Tencel spacer yarn are slightly thicker than the fabrics with cotton spacer yarns.

Figure 3.5 Shrinkage process of a spacer fabric in steaming stage.

3.4 Property evaluation

The performance of the spacer fabrics fabricated was evaluated with different tests which were relevant to the dressing use. These tests included the wettability test, absorbency test, air permeability test and water vapor transmission test which were related to moisture management ability, and thermal property test which was related to thermal insulation performance. Wettability showed how fast the liquid entries spacer fabric. Absorbency not only indicated how much liquid spacer fabric could absorb, but also represented how much liquid could be retained inside spacer zones after draining. The tests for water vapor transmission presented how fast the water evaporated from spacer fabrics, while air permeability test was to determine how difficult the air passed through spacer fabric. All these tests were carried out in the standard atmosphere, which was 20 ºC and 65% RH relative humidity. The details of each testing method are described below.

3.4.1 Wettability test

The wettability test was carried out according to AATCC 79 method. Wetting time of spacer fabrics was tested in the conditioned laboratory with overhead lighting. The 20 cm × 20 cm sample was placed 10 mm below the tip of the burette. A timer was started when one drop of distilled water fell on the fabric surface and stopped when the drop

of water lost its reflectivity. Each sample was tested for five water drop sites and the average values were reported.

3.4.2 Absorbency test

The absorbency of spacer fabrics was tested following British Standard 7959. The objective of absorbency test was to measure the liquid containing in a spacer fabric, which was the key to providing a moist environment for the wound. During the test, the tested sample of 10 cm × 10 cm (100cm^2) was placed on the surface of distilled water. After reaching visual saturation, the tested piece was further immersed in water for 2 min. Then, the sample was removed and drained for 30s. The weight of water absorbed by per 100 cm^2 of the sample was calculated. Five specimens were tested for each type of fabric. The absorbency was calculated according to Equation 3.3.

$$\text{Absorbency } (g/100cm^2) = W_1 - W_0 \qquad \text{Equation 3.3}$$

Where W_0 is the weight of the dry sample (g/100cm^2); W_1 is the weight of the sample with water absorbed (g/100cm^2).

3.4.3 Water vapor transmission rate (WVTR) test

The WVTR test was conducted according to British Standard 7209. Circular specimens with a diameter bigger than the outer diameter of the test dish were first prepared by cutting. Then, 46 cm^3 of water was put into the dish with an inner diameter of 83mm, and each tested specimen was fixed to the rim of the dish using quick-drying adhesive cement. The distance between the surface of the water and the underside of the specimen was 10 ± 1 mm at the beginning of the test. Finally, the dish fixed with fabric was put onto a turntable with a rotation speed of 2 r/min for 24 h. The rotation of dish was to avoid the formation of still air layers above the dish. The mass of the dish with water and fabric sample at the beginning and after 24 h of the test was measured, respectively. The amount of water evaporated per m^2 per 24 h was calculated according to Equation 3.4. Three repeating tests were conducted for each type of fabric.

$$WVTR\ (g/(24h*m^2)) = (M_0-M_1)/A \qquad \text{Equation 3.4}$$

$$A = \pi d^2/4\ (d=0.083m)$$

Where M_0 and M_1 are the masses of the dish with water and fabric sample at the beginning and after 24h of the test (g); A is the evaporation area (m^2); and d is the inner diameter of the dish (m).

3.4.4 Air permeability test

The air permeability test was carried out according to ASTM D737 on an SDL M021S air permeability tester. Each tested specimen was first placed onto the test head of the test instrument. Then, the test was conducted under a water pressure difference of 100Pa. The air permeability result was recorded in SI units of the instrument as $ml/s/cm^2$. Five specimens were tested for each type of fabric.

3.4.5 Thermal property test

A KES-F7 Precise and Fast Thermal Property-Measuring Instrument Thermo Lab II was used to test the thermal property. The sample of 20cm × 20cm was placed onto the testing area of the instrument, and the q-max values (warm/cool feeling evaluation value) with and without samples were measured, respectively. The test for each type of sample was repeated for five times. The rate of heat keeping was calculated according to Equation 3.5.

$$Q\ (\%) = (1 - Q_2/Q_1) \times 100 \qquad \text{Equation 3.5}$$

Where Q_1 is the q-max value without sample placed on the testing area, J/ ºC; Q_2 is the q-max value with sample placed on the testing area, J/ ºC.

3.4.6 Statistical analysis

In order to evaluate the effects of structural and yarn parameters on the properties of spacer fabrics, an N-way analysis of variance (ANOVA) was performed with help of Matlab software. The *p* values were calculated. The higher the *p* value is, the lower the significance is. In this study, $p \leq 0.0500$ indicated that the effects were significant.

3.5 Results and discussion

3.5.1 Wettability and absorbency

The results of the wetting time of all the spacer fabrics are shown in Figure 3.6. A short wetting time implicates good wettability. From Figure 3.6 and the ANOVA results, it can be seen that the wetting time of spacer fabrics was mainly affected by the type of spacer yarns ($p = 0.0019$). The wetting speeds of the fabrics made of Tencel space yarn were much faster than those of the spacer fabric made of cotton spacer yarn. Cotton fiber is a kind of natural fiber with many hydrophobic impurities such as waxiness and cottonseed hulls. Even though most of the impurities are removed from cotton yarn after pretreatment, the wettability of the cotton yarn is still much slower than that of the man-made Tencel yarn. As the Tencel yarn absorbed liquid much faster than cotton yarn, once the water drop contacted with Tencel spacer yarns, it could be drawn quickly from the surface. However, as the surface yarns are made of hydrophobic fiber,

the effects of the number of the surface yarns were not significant (p = 0.8237). Although the wetting time slightly decreased with the increase of spacer yarn connecting distance, the difference was not statistically significant (p = 0.2244).

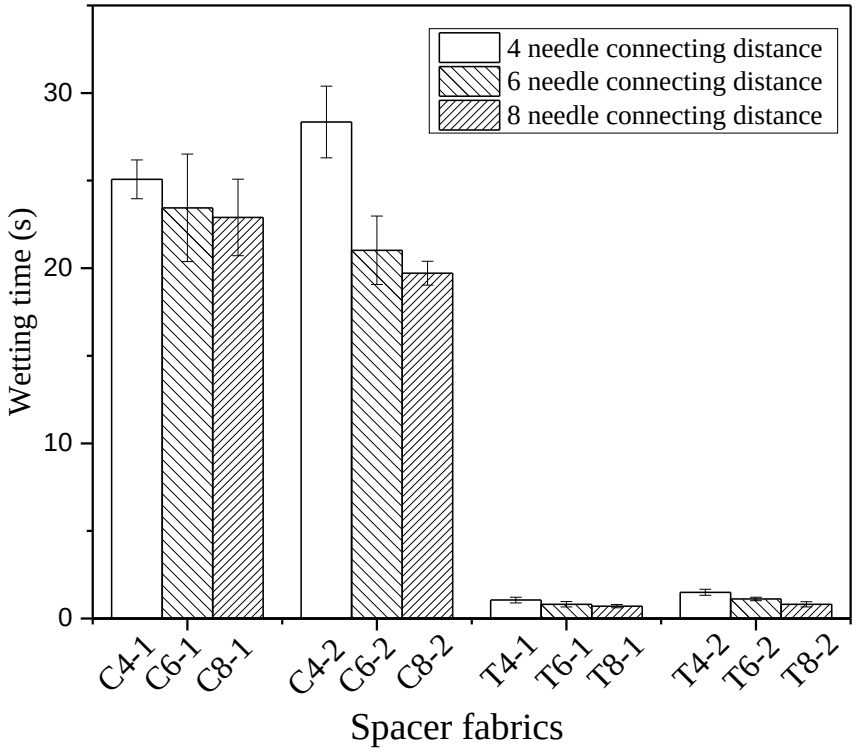


Figure 3.6 Wetting time of spacer fabrics.

The results of the absorbency of all twelve spacer fabrics are shown in Figure 3.7. As the surface layers of all the spacer fabrics were made of elastic synthetic yarns, their absorptive capacity mainly depended on the spacer yarns. From Figure 3.7 and ANOVA results, it can be seen that the amounts of water absorbed increased with the increase of the length of spacer yarns, and the effect was significant (p = 0.0268). At

the same time, the absorbency of spacer fabrics knitted with two surface yarns was also higher than spacer fabrics knitted with one surface yarns. The effect of number of surface yarns on absorbency was significant (p = 0.0407). The main reason is that the increase of both spacer yarn length and surface yarn number leads to an increase of the mass of spacer yarns in per 100cm^2 fabric (Table 3.2), which make fabrics absorbing more water. The more the absorbent spacer yarns are contained in the spacer zone, the better the absorbency is.

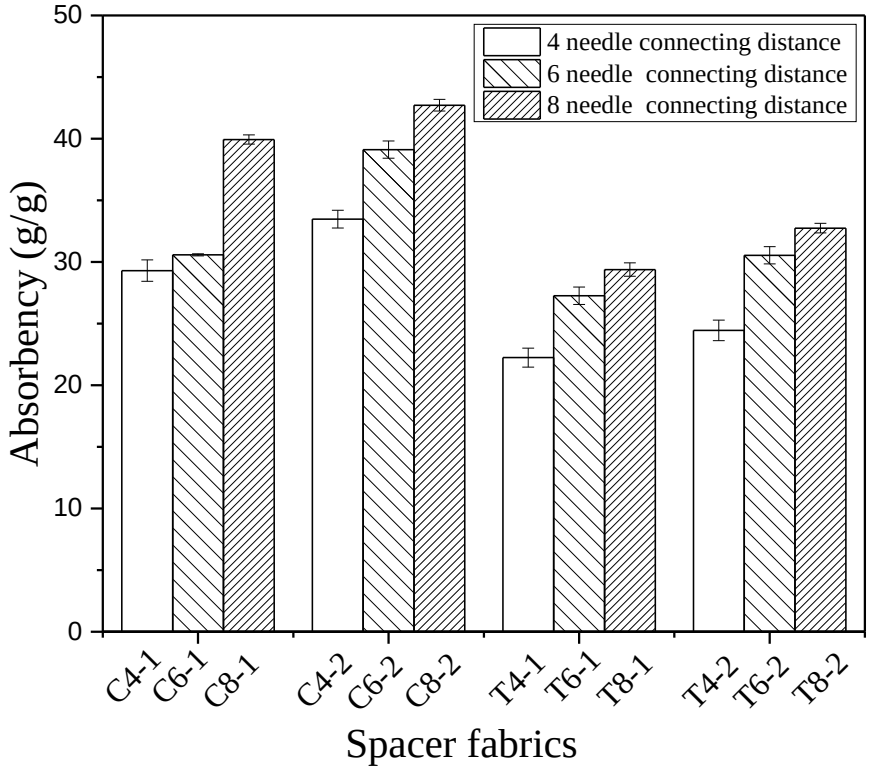


Figure 3.7 Absorbency of spacer fabrics.

The type of spacer yarn materials also had a significant influence on the absorbency of spacer fabrics ($p = 0.0108$). The results show that the spacer fabrics made of Tencel spacer yarn had lower absorbency than the spacer fabrics made of cotton spacer yarn. This implicates that cotton yarn can absorb more liquid than Tencel yarn although the cotton yarn needs much longer time to be wetted. Despite the same chemical compositions of cotton and Tencel (cellulose), Tencel fiber has a higher degree of polymerization and crystallinity because it is man-made fiber. Therefore, cotton fiber can retain more water inside its structure, and the spacer fabrics made of cotton yarn as spacer yarns can provide a better moist environment for wound healing. As the porosity of spacer fabrics mainly presented the space or holes existing in the middle layer, and the wettability is the wetting time after liquid contacting with fabric surface which can hardly be affected by the porosity. Absorbency represents the amount of liquid absorbed by spacer fabrics, higher porosity gave spacer fabric higher ability to absorb water. However, the areal mass of spacer yarns and the type of spacer yarns also affected the absorbency.

The ANOVA results showed that the interactions between the spacer yarn connecting distance and number of surface yarns, the spacer yarn connecting distance and type of spacer yarns, the number of surface yarns and type of spacer yarns did not have significant effects on the wettability ($p = 0.4584$, 0.2909 and 0.6402) and absorbency

(p = 0.4551, 0.3157 and 0.3210). This indicates that the interactions between these parameters were limited.

It should be pointed out that in order to increase the quantity of liquid absorbed by a unit area of spacer fabric for a given type of spacer yarn, two ways can be used. The first way is to increase the stitch density without increasing the fabric thickness to have more fiber material to absorb more liquid. The second way is to increase the fabric thickness keeping the same loop density. However, the increase of both stitch density and thickness will lead to a decrease of air permeability, which leads to a low comfort of spacer fabric. In addition, the keeping of a moist environment also depends on the evaporation of the liquid.

3.5.2 Permeability of water vapor and air

The testing results of WVTR are presented in Figure 3.8. It can be seen that the spacer fabrics knitted with longer spacer yarn connecting distance had lower WVTR. This effect was significant (p = 0.0023). The WVTRs of spacer fabrics with two elastic yarns on the surface are slightly lower than that of fabrics with one surface yarn, and the difference was significant (p = 0.0339). As shown in Table 3.2, these fabrics had lower porosity, higher thickness and areal mass of spacer yarns. The lower porosity implies less space inside the spacer zone and smaller openings on the surface for water

to evaporate. Besides, higher thickness gives water vapor longer distance to pass through and more spacer yarns makes water vapor passing more difficultly. However, the type of spacer yarns had little effect on the WVTR (p = 0.1092). Although the different fiber fineness and cross section of cotton and Tencel yarns (Table 3.2) may have effects on the WVTR, the effects were not significant when applying in a spacer fabric structure.

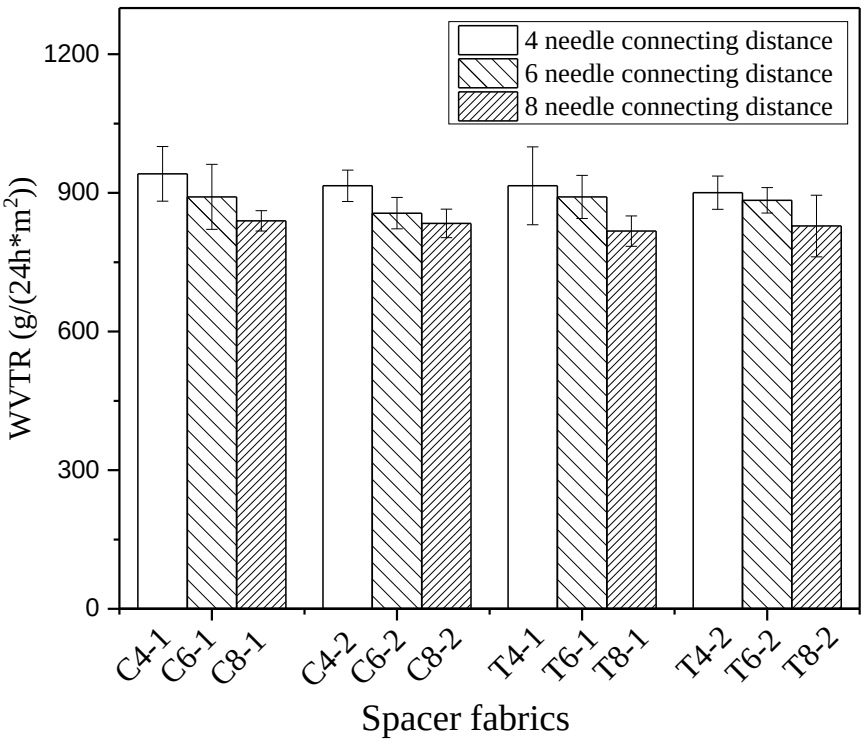


Figure 3.8 WVTR of spacer fabrics.

Considering that a moist environment is required for wound healing, a moderately low WVTR is beneficial to the wound. However, the reduced transmission rate may cause

the surrounding skin wetting for a long time, while the water vapor could not pass through and accumulate on the surface of wound and skin. The WVTRs of wound dressings were suggested to be higher than that of normal skin (200-500 g/(24h*m^2)) to avoid infection [148]. The results show that the WVTRs of all the spacer fabrics were between 800 and 1000 g/(24h*m^2), much higher than that of normal skin. Moreover, the WVTRs of spacer fabrics are definitely lower than that of traditional cotton gauze or normal fabrics because of their higher thickness. In this regard, the WVTRs of spacer fabrics were at a proper medium level and suitable for applying as wound dressings.

The results of air permeability are presented in Figure 3.9. The air permeability of spacer fabrics is highly correlated with their porosity. According to the results, the structures knitted with two polyester/spandex yarns on their surfaces were more impermeable. The effect of number of surface yarns on air permeability was significant (p = 0.0053). This is normal because the use of more elastic yarns in knitting fabric surface makes spacer fabric tighter. There is no doubt that the higher the porosity is and the thinner the fabrics are, the better the air permeability is. The effect of spacer yarn connecting distance on air permeability was not significant (p = 0.2970).

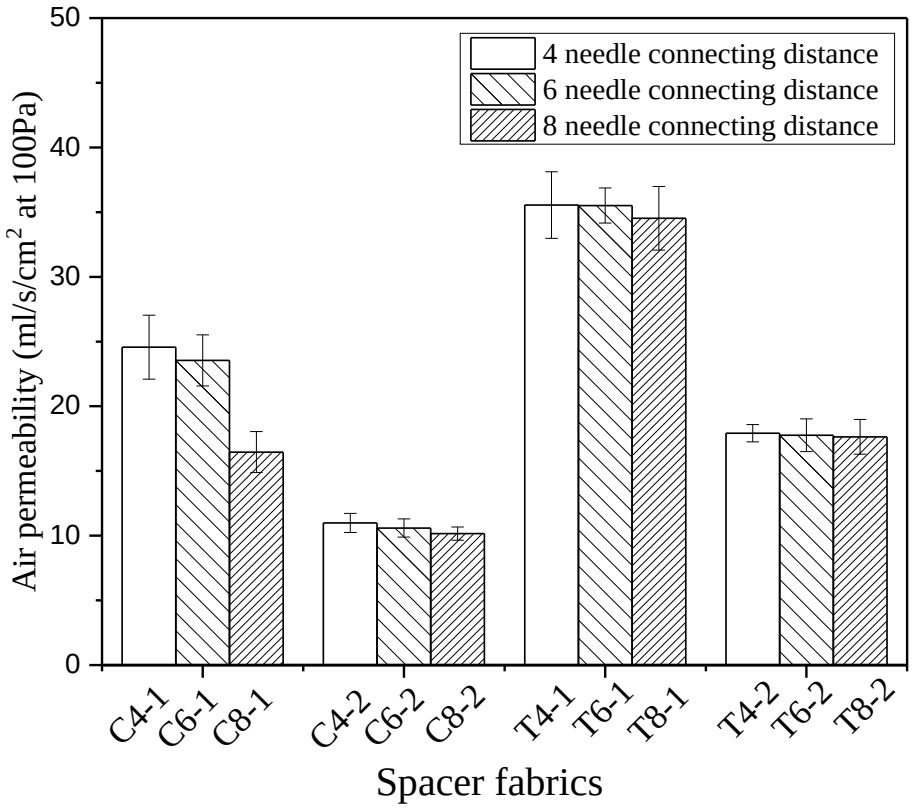


Figure 3.9 Air permeability of spacer fabrics.

From Figure 3.9, it can be also seen that the type of spacer yarns also significantly affected air permeability (p = 0.0097). The air permeability of cotton-yarn spacer fabrics was apparently lower than that of Tencel-yarn spacer fabrics. It is because many fine hairs exist on the cotton fiber surface, which were obstacles for air to go through the fabric. By contrast, the surface of Tencel fiber is relatively smooth. The fine hairs of cotton fiber can be clearly observed in the cross-section pictures of spacer fabrics as shown in Figure 3.4, and the better light reflection of Tencel fiber can explain its smooth surface.

The ANOVA results showed that the interactions between the spacer yarn connecting distance and number of surface yarns, the spacer yarn connecting distance and type of spacer yarns, the number of surface yarns and type of spacer yarns also did not have significant effects on the WVTR (p = 0.0882, 0.0516 and 0.0634) and air permeability (p = 0.3875, 0.4317 and 0.0882). As mentioned above, these parameters were relatively independent and had little interactions in between.

It is commonly believed that anaerobic bacteria are instrumental in the production of volatile odorous molecules [8]. Wound malodor is aggravated by poor air permeability of dressing, which is increasingly becoming a problem especially for patients with chronic wounds. Due to their special textile structures, spacer fabrics had very good air permeability. Noticeably, the sample T4-1 possessed high permeability for both water vapor and air.

3.5.3 Thermal property

Figure 3.10 shows the heat keeping rates of all the spacer fabrics. It is noted that the heat keeping rates rose significantly with the increase of spacer yarn connecting distance (p = 0.0500) and the number of surface yarns (p = 0.0137). Spacer fabrics with longer spacer yarn connecting distance and more surface yarns had lower porosity and higher thickness and areal mass. Therefore the air trapped inside the spacer zone

could be easier kept still, resulting in better thermal insulation. The effect of spacer yarn type on thermal insulation was not significant (p = 0.4123).

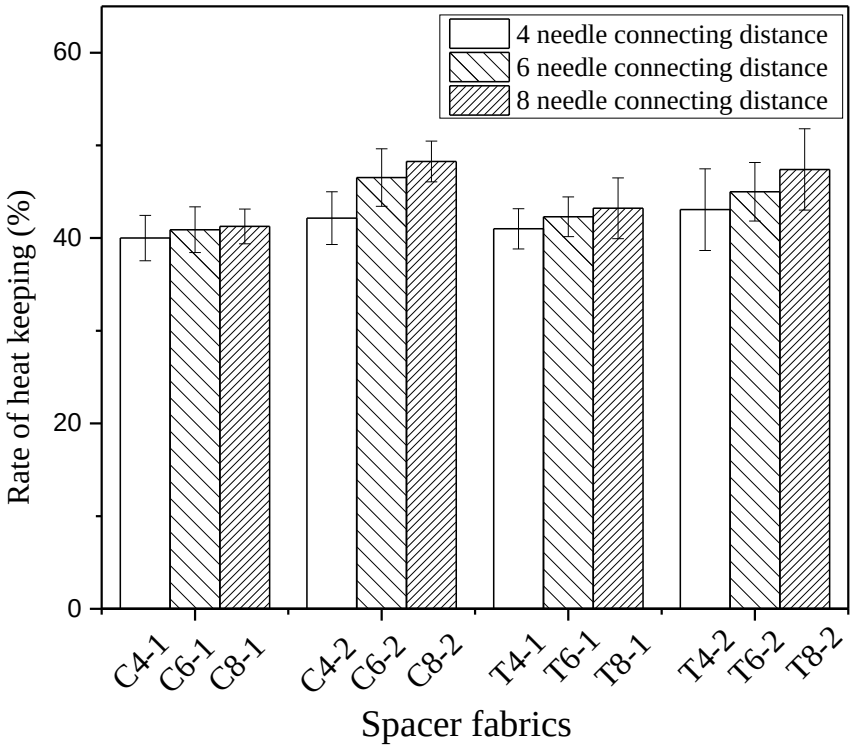


Figure 3.10 Rate of thermal property of spacer fabrics.

The same with other properties, the interactions between the spacer yarn connecting distance and number of surface yarns, the spacer yarn connecting distance and type of spacer yarns, the number of surface yarns and type of spacer yarns also had insignificant effects on the thermal insulation (p = 0.1759, 0.7099 and 0.1726). Dressings with good thermal insulation can keep the wound warm at normal body temperature, ensuring the best condition for cell division and wound healing. The heat

keeping rates of most of the spacer fabrics exceeded 40%, affording an acceptable thermal management property while using as wound dressings.

From the above analyses, it can be found that spacer fabrics C4-1 had very good breathability due to their high porosity, which was beneficial to prevent the wound malodor. Its WVTR was below 1000 g/(24h*m^2), which was lower than that of the foam dressing (around 1000 g/(24h*m^2)) [149] and that of the hydrogel dressing (about 2600 g/(24h*m^2)) [150]. Meanwhile, its thickness was the lowest in all the produced spacer fabrics, which made it more suitable for being used as light wound dressings. By these considerations, spacer fabrics C4-1 was selected as the basic material of absorbent wound dressing for the further study.

3.6 Conclusion

In this chapter, spacer-fabric-based dressing was firstly designed according to the requirements of exuding wound care. Three layers were included in the designed dressing. The wound contact layer should be a hydrophobic with quick moisture transmission rate, and the outer layer should be waterproof to protect the wound. Therefore, its two surfaces were produced with elastic synthetic yarns, and the spacer layer were knitted with absorbent yarns.

Twelve different spacer fabrics were produced and their properties were assessed. The data was analyzed and the *p* values were calculated by using the ANOVA method. Based on the results and analyses, conclusions can be summarized as follows.

a) Fabric thickness and areal mass of spacer fabrics, as well as the areal mass of spacer yarns, increased with the increase of the spacer yarn connecting distance and number of surface yarns. However, the fabric porosity decreases with the increase of the spacer yarn connecting distance and number of surface yarns.

b) Spacer fabrics with longer spacer yarn connecting distance have shorter wetting time, better absorbency and thermal insulation, but have poorer WVTR. The effect of spacer yarn connecting distance on air permeability was not significant.

c) Spacer fabrics knitted with two surface yarns have better absorbency and better thermal property, but have poorer air permeability than spacer fabrics knitted with only one surface yarn.

d) Spacer fabrics knitted with Tencel spacer yarn have much shorter wetting time and better air permeability than spacer fabrics with cotton spacer yarn. However, spacer fabrics with cotton spacer yarns can retain more water inside spacer zone than spacer fabrics with Tencel spacer yarns.

e) The interactions between the spacer yarn connecting distance and number of surface yarns, the spacer yarn connecting distance and type of spacer yarns, the number of surface yarns and type of spacer yarns do not have significant effects on all the properties.

Considering their good air permeability and appropriate absorbency and WVTR, spacer fabric knitted with cotton spacer yarn with 4 needle connecting distance (C4-1) was selected as the basic material of designed dressing. It would be processed with antibacterial treatments and water resistant treatments on the outer layer surface to form the final wound dressing in the following chapters.

Chapter 4 Antimicrobial treatment of spacer fabric

4.1 Introduction

This chapter aims to develop an antimicrobial absorbent wound dressing based on spacer fabric. For exuding wounds or burns, the warm and moist wound healing environment may give large chances to microbial growth [151, 152], which may prolong inflammatory stage and cause infection, even lead to acute wounds convert to hard-to-heal chronic wounds [61]. An ideal dressing should absorb the exudates to provide a balanced moist environment and protect wound from bacterial and other organisms [5]. Since silver is a broad-spectrum antimicrobial agent, a growing number of silver-containing occlusive absorbent wound dressings are developed to keep moisture and prevent microbial growth.

Several products are used to apply silver on dressings, such as silver nitrate, silver sulphadiazine (SSD) [153, 154] and nanocrystalline silver [155]. However, toxicity of silver ions, silver sulphadiazine (SSD) and nanocrystalline silver has recently received much attention. Adverse reactions and side effects of silver sulphadiazine (SSD) have been reported [156, 157]. Toxicity of nanocrystalline silver was observed when applying a silver-coated wound dressing Acticoat (Smith & Nephew, Inc.) on the burn.

The silver levels in plasma and urine were clearly elevated, as well as the liver enzymes [158]. In addition, silver nitrate *in vitro* has shown a negative impact on fibroblasts, [159] hepatocytes [160] and lymphocytes, which delay wound healing. The reduction of Ag^{+} to Ag^{0} on cellulosic fibers simply immersed in solutions of silver nitrate was observed [161]. The application of silver nitrate solution avoids the synthesis and stabilization steps of Ag nanoparticles (AgNPs) and reduces the consumption of reagents, and makes the recycling/reuse of silver salt easier. This also benefits to avoid the uncertainties on the impact of AgNPs on humans and eco-systems [161, 162]. So the silver nitrate solution was used in this study.

Although antibacterial treatments on spacer fabric have been reported, seldom of them designed and manufactured antibacterial spacer fabric specially for wound dressing application. R. Bagherzadeh [163] et al. treated spacer fabric with antibacterial agent and obtained 99.99% reduction in *Staphylococcus aureus*. The whole three layers of this spacer fabric were made of polyester yarns. The spacer fabric was hydrophobic and the concentration of antibacterial agent of each layer has not been reported. In this study, spacer fabric was treated with silver nitrate in a simple pad-to-dry method. The comparison of silver distribution between normal multilayered cotton fabric and spacer fabric was carried out. Spacer fabric is potential to retain the aqueous solution and silver inside its middle layer. The cytotoxicity was reported directly proportional to the silver concentration, thus, low silver concentration on the wound bed may

prevent interference with wound-healing mechanisms [164]. The much lower silver concentration of wound contact layer makes spacer fabric a suitable material to prevent silver toxicity and wound-healing delay. In addition, the analysis of chemical distribution on spacer fabric has seldom been reported. Based on the quantitative analysis method of chemicals on spacer fabric, changes of three-dimensional structure of spacer fabric according to the wound care requirements could be easily performed.

4.2 Experimental

4.2.1 Materials

Spacer fabric C4-1 was used in the antimicrobial treatment (Figure 4.1(a)). The area of each spacer fabric was 9 cm × 18 cm, and the mass was 8.75 ± 0.35 g. The areal mass of spacer fabric was 540.4 ± 21.4 g/m^2. The surface fabric density of spacer fabric was 8.6 wales/cm in course direction and 13.0 courses/cm in wale direction (Table 3.2). To compare the absorption of silver solution in the antimicrobial treatment between multilayered fabrics, the generic 4-layered cotton fabric was used to compare with the spacer fabric. The reason for using 4-layered cotton fabric is that the fabric is commonly applied for absorption in our daily life and the absorbent layer of spacer fabric was also made of cotton. The 4-layered cotton fabric consisted of 4 loose woven layers which were sewn together in a corner (Figure 4.1 (b)). The woven fabric was produced with 16.3 tex cotton yarns in warp (16 threads/cm) and 24.5 tex cotton yarns

in weft (12 threads/cm). The 4-layered fabric was bleached. The area of cotton fabric was 18 cm × 18 cm, and the mass was 7.08 ± 0.08 g.

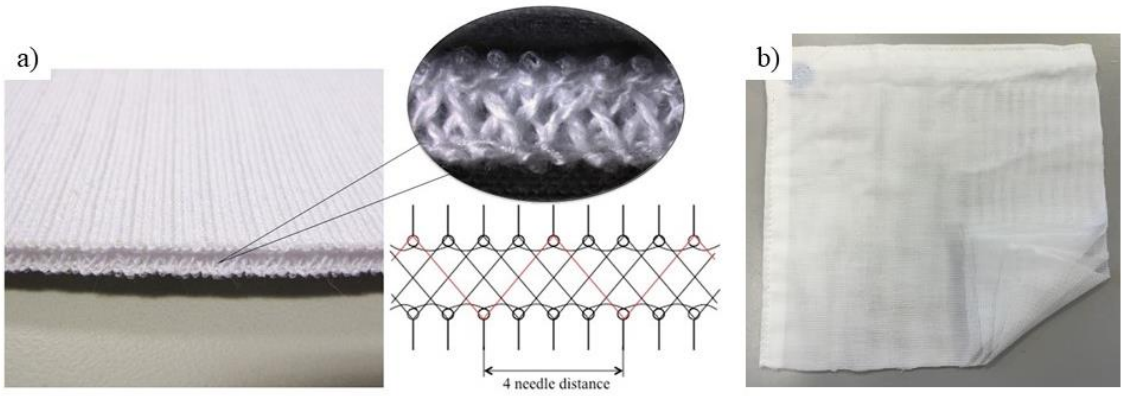


Figure 4.1 a) spacer fabric and its cross section and b) 4-layered cotton fabric.

The thickness of materials was measured by using material testing equipment D-6940 from Karl Schröder KG, Germany. The 4-layered cotton fabric was made of 100% cotton, so the density of fibers of 4-layered cotton fabric (ρ) is 1.54 g/cm^3. The porosity of fabric was measured as Equation 3.2 described in section 3.3. The density of fabric was calculated as Equation 4.1.

$$\text{Density (g/cm}^3\text{)} = W_m/V_m \qquad \text{Equation 4.1}$$

W_m is the mass of fabric (g), V_m is the total volume of fabric (cm^3).

4.2.2 Impregnation of fabrics

A solution of 1 g/L $AgNO_3$ (analytical grade, from VWR Austria) was prepared. The pH of the solution was adjusted to 6 by using 9.814 g/L (0.1M) CH_3COOK (99%, from Carl Roth GmbH, Austria) as a buffer. Each fabric was immersed in 500 ml solution at 40 ºC for 1h. Then, fabrics were padded (type HVF-33593 padder from Werner Mathis AG) with 1 bar padding pressure and dried at 60 ºC. As the thicknesses of 4-layered cotton fabric and spacer fabric were different, the completely drying time for them was different. The 4-layered cotton fabric was dried for 5 min and the spacer fabric was dried for 30 min. The layer on the top when padding and drying was marked as top layer, and the layer on the bottom when padding and drying was marked as bottom layer for the following tests.

The spacer fabric was equally treated with ammonium to compare its antibacterial effects with the spacer fabric treated with silver. A solution of 0.5 wt% dimethyloctadecyl [3-(trimethoxysilyl)propyl] ammonium chloride (60 wt% solution in MeOH, purchased from J&K Hong Kong) was used. The spacer fabric was immersed in room temperature for 30 min and padded with 1 bar padding pressure. Then, the fabric was dried at 95 ºC for 15 min and cured at 130 ºC for 3 min.

The absorbency of silver solution was tested through impregnating fabrics in 1 g/L $AgNO_3$ solution for 1h and then draining for 10 min. The absorbency per gram fabric was calculated as Equation 4.2.

$$\text{Absorbency of silver solution (g/g)} = (W_2-W_1)/W_1 \qquad \text{Equation 4.2}$$

where W_1 is the mass of conditioned dry sample (g) and W_2 is the mass of immerse d sample (g).

The padding add-on for each fabric was calculated according to Equation 4.3.

$$\text{Add-on (\%)} = (M_2-M_1)/M_1 \times 100\% \qquad \text{Equation 4.3}$$

where M_1 is the mass of conditioned dry sample (g) and M_2 is the mass of padded sample (g).

The padding add-on of a single layer of the spacer fabric was calculated through the percentage of silver content on this layer. The add-on of a layer was calculated as Equation 4.4.

$$\text{The add-on of a layer (\%)} = [S]_1/[S]_0 \times P \qquad \text{Equation 4.4}$$

where $[S]_1$ is the silver content of this layer (mg/g), $[S]_0$ is the silver content of the whole fabric (mg/g) and P is the add-on of the whole fabric (%).

4.2.3 Property evaluation

4.2.3.1Silver content test

Three positions of 9 cm × 1.5 cm from each fabric were selected to be measured in the silver content tests. In order to guarantee that the silver contents of the selected positions represented the silver content of the whole fabric, the selection of testing areas in 4-layered cotton fabric and spacer fabric are shown in Figure 4.2, respectively. The different layers of the spacer fabric were separated by cutting off the two surface layers as shown in Figure 4.3. The loop heads of cotton yarns and surface polyester/spandex yarns were cut off.

The extracted silver from each fabric was measured. A layer of 9 cm × 1.5 cm fabric was immersed in 25 ml of 15 wt% HNO_3 (65%, from Merck, Austria) for 2 h at 80 ^oC. Silver concentration was analyzed using a flame atomic absorption spectroscopy (AAS, Z-8230 polarized Zeeman atomic absorption, Hitachi, Japan) equipped with a silver lamp at 328.1 nm wavelength.

Calibration solutions were made in range of 1 - 5 mg/L Ag^+ using $AgNO_3$. 15 wt% HNO_3 was added to dissolve any impurities or precipitate, and 5 wt% CH_3COOH (96%, from Merck, Austria) was added to prevent the reduction of Ag^+. For each measurement of silver content using AAS, a calibration curve was employed. The silver contents from fabrics were calculated from the regression. The silver contents by per gram fabric are presented in this study. In addition, the original $AgNO_3$ solution (before treatment) and residual $AgNO_3$ solution (after immersion) were diluted and their silver concentrations were measured by AAS method.

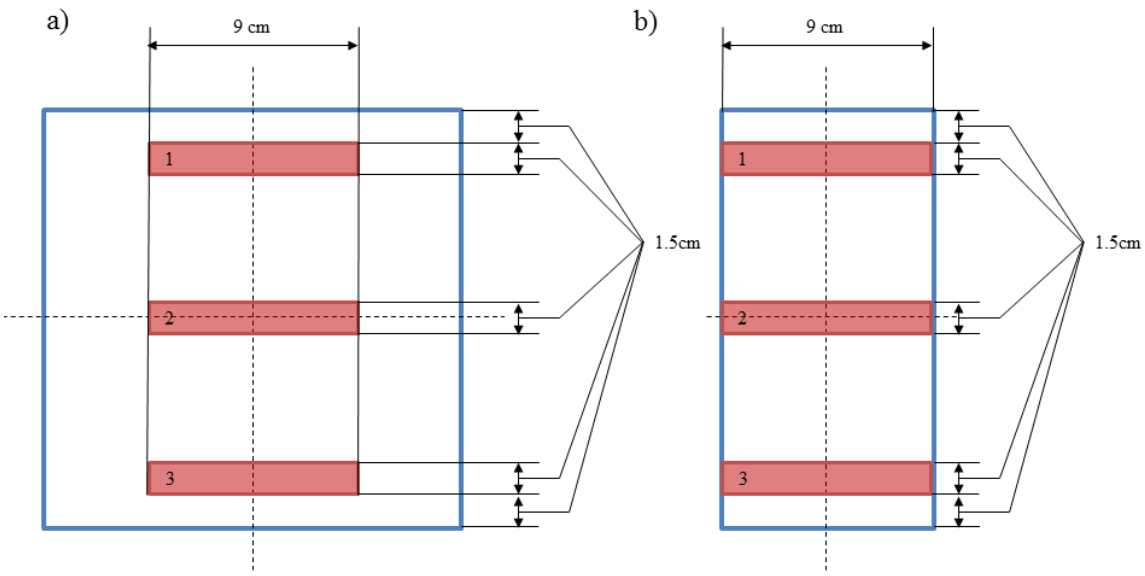


Figure 4.2 The positions selected for silver content tests in (a) 4-layered cotton fabric and (b) spacer fabric.

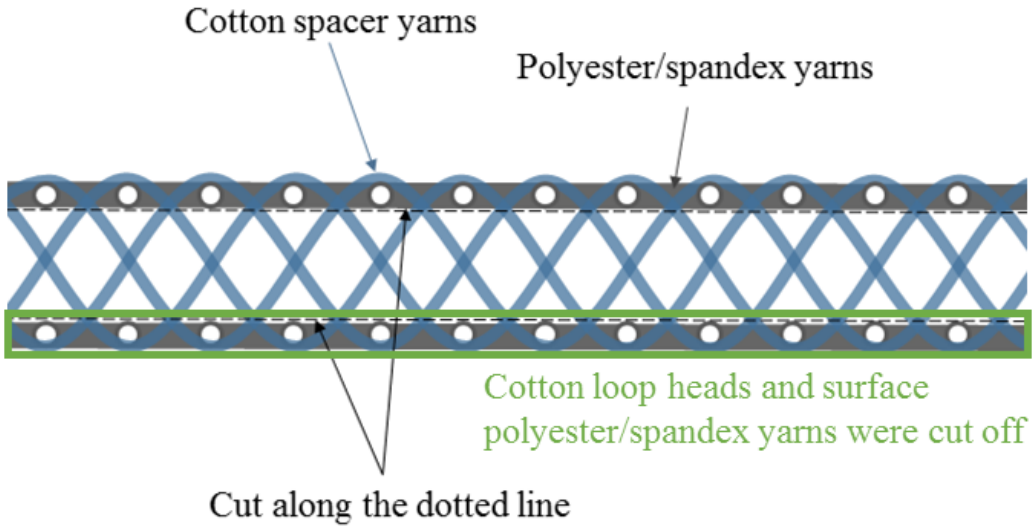


Figure 4.3 The cross-sectional schematic diagram of the spacer fabric.

4.2.3.2 Antibacterial activity test

The antibacterial activity tests were performed using the standard test method for the determination of the antimicrobial activity of immobilized antimicrobial agents under dynamic contact conditions (ASTM E2149-01). Two kinds of bacterium were used in this test, gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae*. *Staphylococcus aureus* are often found on the skin, and *Klebsiella* species are a major cause of wound infection, especially in burn patients.

Briefly, a specimen was measured by weight and 2 g were placed in 250 ml wide-necked, screw-capped Erlenmeyer flasks containing 50 ml of a suspension of *Staphylococcus aureus* ATCC 6538 or *Klebsiella pneumoniae* ATCC 4352 (approx.

3.0 x 10^5 cells per ml) in 0.3 mM KH_2PO_4 buffer solution (pH 7.2). Flasks were vigorously shaken for intervals of 0 min, 1h, 3h, 6h and 24h at 25°C. At the end of each time interval 1 ml of bacterial suspension was removed, serial diluted and plated on nutrient agar. The bacteria were incubated at 37°C for 24h and the number of viable cells (CFU) was determined. The antibacterial activity was evaluated by calculating the reduction of bacteria according to Equation 4.5.

$$R\ (\%) = (A-B)/A \times 100\% \qquad \text{Equation 4.5}$$

where R is the percentage of reduction bacteria viability (%). For the calculation of the control fabrics (untreated samples), A is the number of viable bacteria (CFU/ml) at contact time = 0 and B is the number of viable bacteria (CFU/ml) after contact time = x h. For the calculation of the treated samples (CFU/ml), A is the number of viable bacteria (CFU/ml) of the untreated fabrics at contact time = x h, and B is the number of viable bacteria (CFU/ml) after contact time = x h with silver-containing fabrics. According to the ASTME2149-01 method, two replicates were made.

4.3 Results and discussion

4.3.1 Silver absorption and distribution

The silver absorption behavior of spacer fabric was compared with that of 4-layered cotton fabric. The results are presented in Table 4.1. As the porosity of spacer fabric was higher than that of 4-layered cotton fabric and the density of spacer fabric was lower than that of 4-layered cotton fabric, the absorbency of per gram spacer fabric are higher than that of per gram 4-layered cotton fabric. Also, the silver content of spacer fabric was higher than that of 4-layered cotton fabric. Since the yarns and fabrics had not been treated with active agents, the affinity of fabric to silver was weak. Therefore, the silver content of fabric mainly depended on the absorbency. The three-dimensional structure of spacer fabric increased the porosity comparing with the layer-by-layer structure of 4-layered cotton fabric, which led to a higher absorbency and silver content of spacer fabric. In addition, the spacer yarns in the vertical direction gave spacer fabric higher compression resistance than 4-layered cotton fabric, which in turn raised silver content of spacer fabric.

The silver distributions on each layer of spacer fabric and 4-layered cotton fabric are shown in Figure 4.4. The add-on percentage of each layer of the spacer fabric is presented in Table 4.2. As the findings reveal, the silver contents of middle layers of

4-layerd cotton fabric were lower than that of surface layers, whereas the middle layer of the spacer fabric had a much higher silver content than its two surface layers.

Table 4.1 The comparison between spacer fabric and 4-layered cotton fabric.

	Spacer fabric	4-layered cotton fabric
Thickness (mm)	3.25 (± 0.09)	0.94 (± 0.05)
Density (g/cm^3)	0.166 (± 0.002)	0.229 (± 0.003)
Porosity (%)	89.0 (± 0.5)	85.1 (± 0.5)
Absorbency of silver solution (g/g)	3.75 (± 0.15)	3.13 (± 0.07)
Add-on (%)	289.19 (± 5.92)	155.36 (± 8.77)
Silver content (mg/g)	1.88 (± 0.13)	1.05 (± 0.02)

Note: Standard deviations are given in parentheses.

Both spacer fabric and 4-layered cotton fabric were immersed in $AgNO_3$ solution for 1 h. The fabrics were fully submersed and completely saturated. As 4-layered cotton fabric was made of 100% cotton, theoretically all its layers should have the same silver contents. However, the 4-layered cotton fabric was dried in the horizontal state, which made the surface layers the evaporation fronts. Therefore, migration of silver ions was occurring during drying, causing higher silver contents in the surface layers of 4-layered cotton fabric. For spacer fabric, the cotton core was holding the silver, while the top and bottom hydrophobic layers had a very small concentration. The wetting

gradient [165] (hydrophobic to hydrophilic) along the thickness direction transfers $AgNO_3$ solution from the surface layers to the middle layer. This differential capillary effect also kept liquid in the hydrophilic middle layer instead of reverse movement. With the hydrophobic polyester/spandex surface layers, it was possible to get the core of the structure saturated with silver. This was the desired effect that reduced the silver residual of the surface layer.

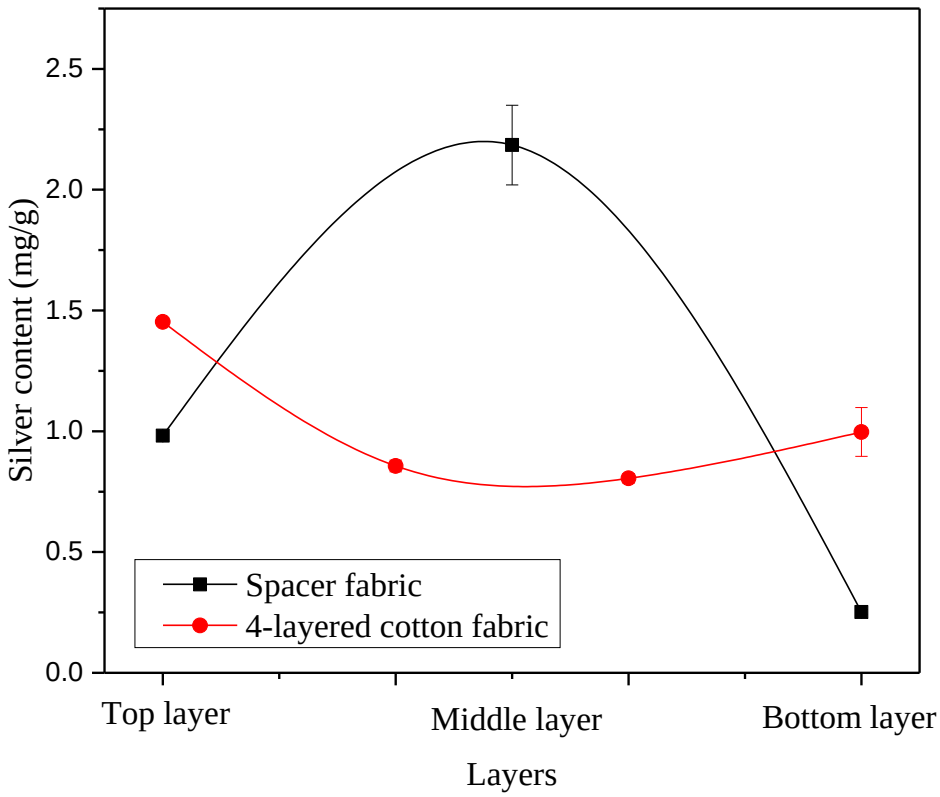


Figure 4.4 Silver distributions on each layer of 4-layered fabrics and spacer fabric.

Table 4.2 The add-on percentage of each layer of the spacer fabric.

	Add-on (%)
Top layer	155.76 (± 3.29)
Middle layer	346.58 (± 6.74)
Bottom layer	39.91 (± 1.08)

Note: Standard deviations are given in parentheses.

4.3.2 Antimicrobial properties

The antibacterial activities of silver-containing spacer fabric were determined against the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae*. The results are presented in Table 4.3 and Table 4.4. Both untreated fabrics and fabrics treated with the chemicals without silver were used to identify possible antibacterial activity of the materials to fabricate the fabrics and other chemicals added on the fabrics through treatments. As can be seen in Table 4.3 and Table 4.4, under the test conditions, both the fabric material itself and the chemicals without silver did not cause a significant reduction in bacterial viability. All silver-containing samples exhibited antimicrobial activity for both the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae*. 100% reductions in viability were observed on spacer fabric after less than 1 h, the same as 4-layered cotton fabric. The silver ions could readily bind with negative charged

proteins, DNA, RNA in microorganisms and therefore kill them to achieve the antimicrobial efficiency.

Table 4.3 Reduction in bacterial viability of *Staphylococcus aureus* as a function of time.

	Bacterial reduction (%)			
	1h	3h	6h	24h
Blank	0	0	0	0
Untreated 4-layered cotton fabric	0	0	0	0
Untreated spacer fabric	0	0	0	0
4-layered cotton fabric treated with chemicals without silver	0	0	0	0
Spacer fabric treated with chemicals without silver	0	0	0	0
4-layered cotton fabric treated with silver	100	100	100	100
Spacer fabric treated with silver	100	100	100	100
Spacer fabric treated with ammonium	100	100	100	100

Table 4.4 Reduction in bacterial viability of *Klebsiella pneumoniae* as a function of time.

	Bacterial reduction (%)			
	1h	3h	6h	24h
Blank	0	0	0	0
Untreated 4-layered cotton fabric	0	0	0	0
Untreated spacer fabric	0	0	0	0
4-layered cotton fabric treated with chemicals without silver	0	0	0	0
Spacer fabric treated with chemicals without silver	0	0	0	0
4-layered cotton fabric treated with silver	100	100	100	100
Spacer fabric treated with silver	100	100	100	100
Spacer fabric treated with ammonium	100	100	100	100

Dimethyloctadecyl [3-(trimethoxysilyl)propyl] ammonium chloride is commonly used as an antibacterial agent. The reduction in bacterial viability of the spacer fabric treated with silver was the same with that of the spacer fabric treated with ammonium, indicating that the silver on the treated spacer fabric presented highly efficient antimicrobial properties. The reported highest minimal inhibitory concentrations (MICs) of ionic silver for *Staphylococcus aureus* and *Escherichia coli* is 2.5 μg silver/mL. [166-168] The silver content of the spacer fabric was 1.88 mg per gram fabric. In the antibacterial activity tests, 2 g specimen were placed in a flask containing 50 ml of a suspension of *Staphylococcus aureus* or *Klebsiella pneumoniae*. Under the test conditions applied in this work, the silver concentration in the testing solution was 75.2 μg/mL by calculation which was much higher than the value of MIC. This also explains the high antimicrobial efficiency of the fabric. The silver content could be lowered by reducing the silver concentration of treatment solution to balance the silver costs and the antibacterial efficiency.

The antimicrobial process of applying the silver-containing spacer fabric as a wound dressing is demonstrated in Figure 4.5. When the spacer fabric was applied on a wound, the exudates from wound could be quickly absorbed into the middle layer of the spacer fabric. The exudates were maintained in this layer and silver ions could kill bacteria in the exudates. The silver ions would be kept in the middle layer of spacer fabric. This

could reduce silver concentration on the wound bed, therefore reduce wound healing delay caused by silver. As silver ions could only move when fabric was wetted by exudates, silver mobility would be limited if the exudates were retained in the middle layer. The bottom layer was knitted with hydrophobic polyester/spandex yarns, while the middle layer was knitted with hydrophilic cotton yarns. The wetting gradient not only transferred exudates from the bottom layer to the middle layer, but also kept liquid in the cotton middle layer instead of reverse movement. In this way, most silver ions could be kept away from the bottom layer. The migration of silver ions could also be changed by chemical binders, which should allow the moisture to transfer but not the silver ions.

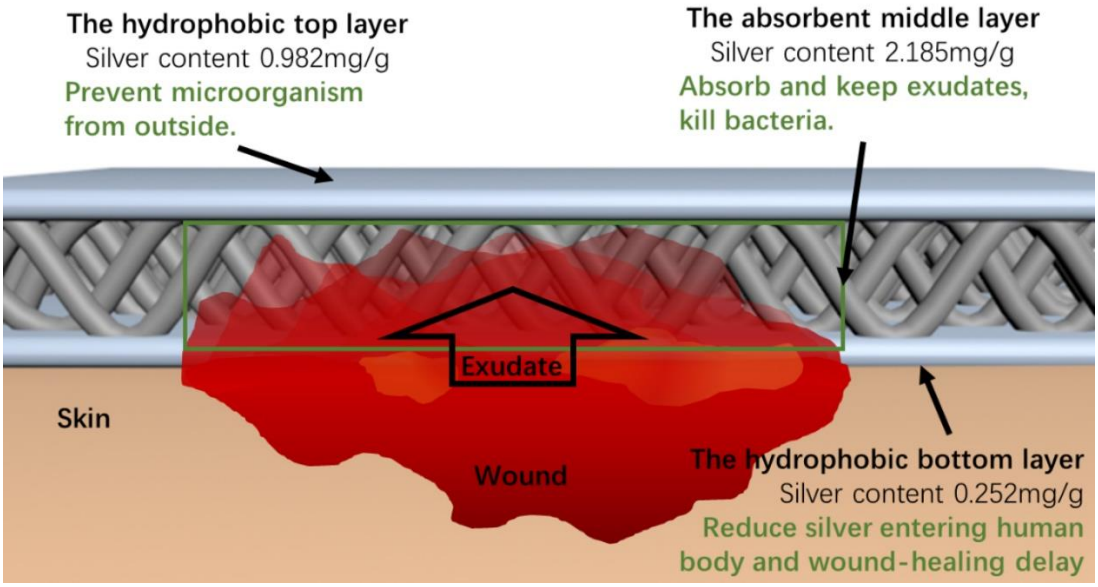


Figure 4.5 The antimicrobial process of applying the silver-containing spacer fabric as a wound dressing.

4.4 Conclusion

In this chapter, a silver-containing spacer fabric was manufactured and analyzed. The silver distributions were compared between the spacer fabric and 4-layered cotton fabric. The results have shown that the silver contents of middle layers of the 4-layerd cotton fabric were lower than their surface layers, whereas the middle layer of the spacer fabric had much higher silver content than its two surface layers. The difference of the silver distribution in the spacer fabric was primarily due to the different absorbency and capillary of materials used in each layer of the spacer fabric and the special three-dimensional structure of spacer fabric. For the antimicrobial properties of silver-containing spacer fabrics, 100% reductions in viability were observed for both the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae* after only 1 h.

As the silver ions could be kept in the middle layer, the bacteria would be killed in the middle layer of dressing. The way to absorb wound exudates and kill bacteria within the dressings reduces silver concentration on the wound bed, and therefore this could be an efficient way to lower the potential of silver entering human body, and prevent the silver toxicity and wound-healing delay.

Chapter 5 Water resistant treatment of spacer fabric

5.1 Introduction

Since a wound dressing performs like skin to prevent contaminated fluid and harmful substance to have access to the wound, the use of weft-knitted spacer fabrics as absorbent wound dressing for promoting wound healing requires them to be capable of adequate capacity in water resistance. As designed in chapter 3, the top layer of spacer fabric should be water resistant to keep fluid away from the wound. In previous chapters, works focus on the fabrication and treatment of a whole fabric, the study moves to the treatment on the surface of spacer fabric in this chapter.

It has been confirmed that a great amount of waterproof products, especially waterproof coatings, are non-permeable or have very low air and water vapor transmission. Spacer-fabric-based dressings for exuding wounds should offer good permeability to avoid malodor and maceration. Therefore, water resistant treatments with good air permeability are the eligible treating methods.

This chapter describes three kinds of water resistant treatments on spacer fabric, including treatment with electrospun nanofibrous membrane, fluorocarbons and TiO_2

nanosol. All the water resistant treatments were carried out on the top layer of spacer fabric. The aims of these methods were not only to make the spacer-fabric-based wound dressings water resistant, but also to keep the good air permeability of spacer fabric. The evaluation of the performance of the water resistant treatments were accordingly presented by water contact angle test and air permeability test. The water resistant chemicals and processing conditions were assessed to select the most suitable method.

5.2 Experimental

5.2.1 Treatment with electrospun nanofibrous membrane

5.2.1.1 Fabrication of electrospun nanofibrous membrane

Spacer fabric C4-1was treated with electrospun nanofibrous membrane. As described in Chapter 4, it was produced by using a single polyester/spandex (100D/40D) yarn to knit the two outer layers, and 32S/2 bleached cotton yarn to knit the spacer layer with a connecting distance of 4 needles. After knitting, the spacer fabrics were steamed and then conditioned at 20 ^{o}C and 65% RH for a week.

Polyurethane and polystyrene were selected for covering nanofibrous membranes onto the top layer of spacer fabric. While the 20 wt % polystyrene electrospinning solution

was prepared by dissolving 20g polystyrene (average Mw ~350,000, average Mn ~170,000, purchased from Sigma-Alorich Co. LLC) in 80g N,N-Dimethylformamide (DMF, GR grade, purchased from Duksan Pure Chemicals Co., Ltd.), the 11 wt % polyurethane electrospinning solution was prepared by dissolving 10g polyurethane (average Mw ~ 600,000, purchased from Hong Kong Hi-Tech Enterprises Ltd.) in 90g DMF. The fabrication process of the nanofibrous membrane on a spacer fabric is schematically shown in Figure 5.1. It was performed on an electrospinning apparatus purchased from Micro & Technologies Expert (TL-Pro), Shenzhen, China. As shown in Figure 5.1, the prepared solution was added to a 20 ml syringe, and the flow rate of 1.1 ml/h was controlled through a syringe pump. A high positive voltage of 16 kV was applied to the needle while the solution was spraying out of the needle to form nanofibers. The polystyrene was sprayed for 30 min, and the polyurethane was sprayed for 1h. The polystyrene or polyurethane nanofibers were collected on the spacer fabric that was adhesive to a drum rotating at a rotating speed of 500 rpm. The electrospinning process was conducted under an environment of 25 ^{o}C and 65 RH%. After completing the electrospinning process, the nanofibrous membrane covered on the spacer fabric was air-dried for about 24h.

Spacer fabric C4-1 treated with polystyrene and polyurethane was named as treated spacer fabric A (TSF A) and TSF B, respectively. Because the thickness and weight of electrospun nanofibrous membrane could be negligible, the thickness and areal mass

of TSF A and TSF B were the same as those of spacer fabric C4-1, which was 3.253 mm and 540.4 g/m^2, respectively.

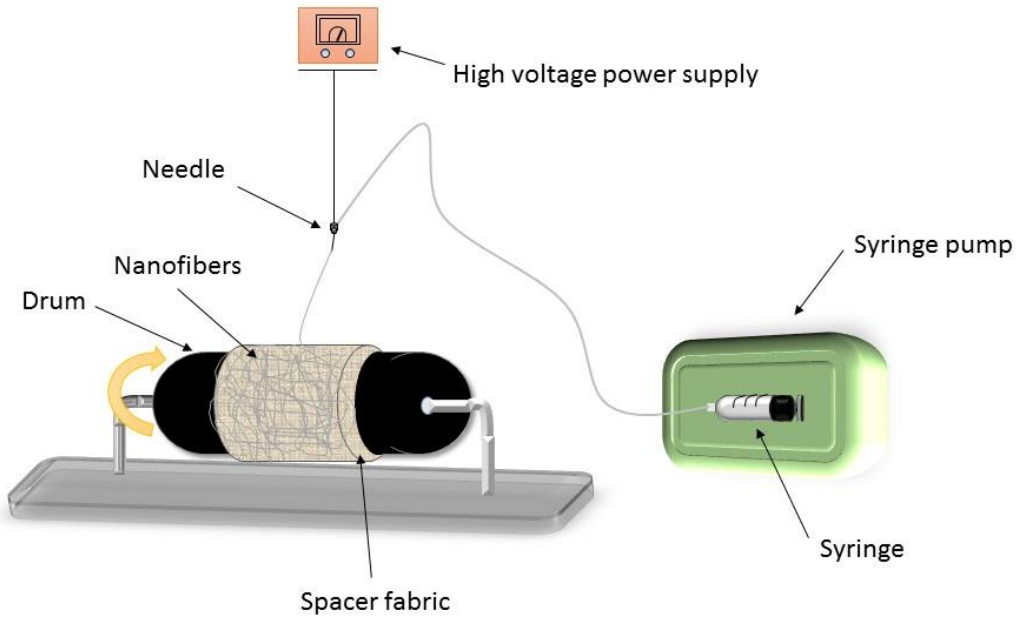


Figure 5.1 Fabrication process of the electrospun nanofibrous membrane on spacer fabric.

5.2.1.2 Characterization of electrospun nanofiber membrane

The chemical structures and function groups of electrospun nanofiber membranes were characterized via Perkin-Elmer Spectrum 100 on an FT-IR Spectrometer made in the USA in a range of 650 ~ 4000 cm^{-1} at room temperature.

The morphologies of electrospun nanofibrous membranes were observed by field emission scanning electron microscopy (FE-SEM) on a Jeol 6490 microscope. Prior to observation, samples were fixed on the sample stage using an electroconductive double-tape and then a layer of gold was sputtered on the surface of samples. These samples were observed in vacuum condition by FE-SEM and their images were recorded.

5.2.2 Treatment with fluorocarbons

NUVA N2114 water resistant agent produced by Clariant Ltd was treated on the top layer of spacer fabric C4-1. The NUVA N2114 solution of concentration 5% ~ 20% was sprayed on the surface of spacer fabric C4-1. A spraying equipment (HD-130, RUIYI, Taiwan) was used at a pressure of 0.4MPa and the moving rate was about 5mm/s. After spraying, the spacer fabrics were cured at 120 ~ 150 ºC for 3 ~ 20 min. The solution concentration, curing temperature and curing time were optimized according to their water contact angle and air permeability.

5.2.3 Treatment with TiO_2 nanosol

5.2.3.1 Synthesis of TiO_2 nanosol

The preparation of TiO_2 nanosol using the hydrolysis of a TTIP hydrosol referred to the literature [137]. First, 40 g TTIP was added dropwise into 100 ml of distilled water solution containing HAc (0.5 wt %) and HCl (1 wt %) under vigorous mechanical stirring. The prepared TTIP hydrosol was then dropped slowly with simultaneous addition of water at 83 ~ 90°C for 4 h to produce a milk-like sol. Subsequently, the sol was cooled to 60°C and stirred violently for 15 h until a transparent bluish sol was obtained. Finally, the mixture was cooled in air to room temperature and aged for 2 weeks, resulting in the final TiO_2 nanosol, which had a TiO_2 solid content of 10 wt %. The above TiO_2 sol was diluted 10-fold and the concentration of 1 wt % was obtained.

5.2.3.2 Fabrication of water resistant fabrics with TiO_2 nanosol

The prepared TiO_2 nanosol solution of concentration 1 wt % was sprayed on the surface of spacer fabric C4-1 to obtain water resistance. A spraying equipment (HD-130, RUIYI, Taiwan) was used at a pressure of 0.4MPa and the moving rate was about 5mm/s. After spraying, the spacer fabrics were dried at 80°C for 3 min and then cured at 160 ^{o}C for 3 ~ 15 min. The curing time were selected based on its effects on water contact angle and air permeability.

5.2.4 Property evaluation

5.2.4.1 Water contact angle test

Water contact angle tests were carried out on the top layer of dressing using contact angle system OCA (Data Physics, Germany). A drop of 2 μl deionized water was dropped onto the sample surface, and a movie was recorded. Pictures of water contact with sample immediately (0s) and after 10s and 30s were captured from the movie. The water contact angles were measured at the three time points for each specimen. Five specimens were used for each type of dressing.

5.2.4.2 Air permeability test

The air permeability testing method of dressings was the same as described in section 3.4.4. The wound contact layer (layer without treatment) faces down to encounter the flow of air at the first place. Five specimens were used for each type of dressings.

5.3 Results and discussion

5.3.1 Treatment with electrospun nanofibrous membrane

5.3.1.1 Structures and morphologies of polystyrene and polyurethane nanofibrous membranes

Polystyrene and polyurethane solution was sprayed onto spacer fabric by electrospinning method to form a water resistant surface. As shown in Figure 5.2, a continuous membrane was formed and covered on the outer layer surface of spacer fabric. The polyurethane nanofibrous membranes can form a better film and have better adhesion on the fabric surface than polystyrene membranes. However, the adhesion between the film and spacer fabric was weak. FT-IR spectra of polystyrene and polyurethane nanofibrous membranes are shown in Figure 5.3. In the FT-IR spectra of polystyrene, the absorption bands at 2922 and 2852 cm^{-1} were the asymmetric and symmetric stretching vibrations of $-CH_2$. The peaks at 1492 and 1452 cuold result from the vibration of C-C of the benzene ring. The absorption bands in 690 ~ 790 cm^{-1} region were caused by C-H of the benzene ring. In the FT-IR spectra of polyurethane, a strong absorbing peak appears at 1729.26 cm^{-1} owing to the stretching vibration of C=O bond in carbamate (R-NH-C(=O)-O-R). There was a peak at 1703.49 cm^{-1} attributed to C=O stretch of amido ester. The wide 1105 ~ 1066 cm^{-1} region was caused by the C-O-C asymmetrical flexing vibration.

The SEM images of the polystyrene and polyurethane nanofibrous membranes are shown in Figure 5.4. It can be seen that nanofibers were interlaced together. The diameters of polystyrene nanofibers were bigger than 2 μm. They were large but distributed evenly. Polyurethane nanofibers were fine with diameters less than 1 μm. The polyurethane nanofibers are not uniform in their diameter. This was because the viscosity of polyurethane solution and the electrospun voltage (15 kV) were relatively high. However, no obvious beads and beaded nanofibers were found in both types of the two membranes. The denser structure of polyurethane membrane made its air permeability lower than polystyrene membrane.

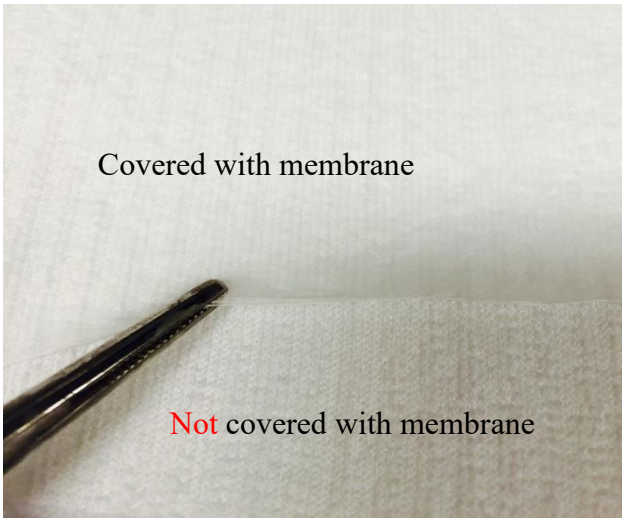


Figure 5.2 Covering of the electrospun nanofibrous membrane onto spacer fabric.

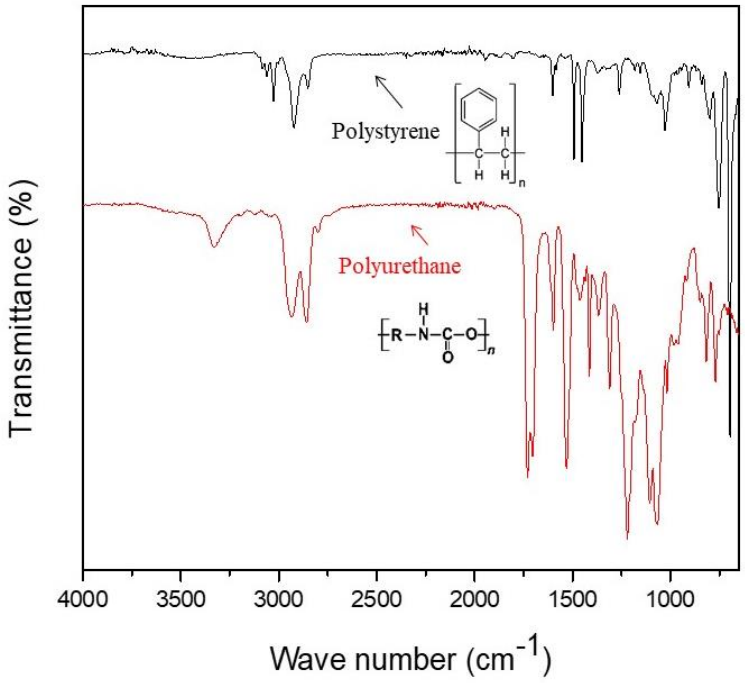


Figure 5.3 FT-IR spectra of polystyrene and polyurethane electrospun nanofibrous membrane.

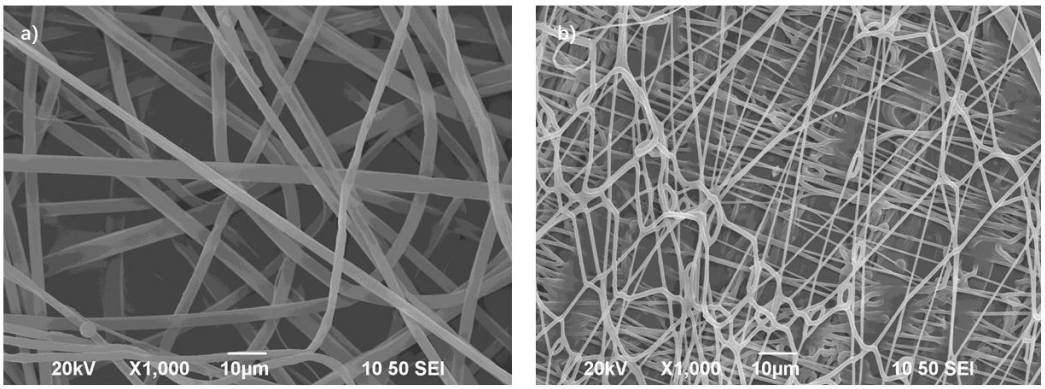


Figure 5.4 SEM images of a) polystyrene and b) polyurethane electrospun nanofibrous membranes.

5.3.1.2 Water contact angle

The water contact angles after 0s, 10s, 30s of the treated spacer fabrics are shown in Figure 5.5. The images of water drops contacting with dressings after 0s, 10s, 30s are presented in Figure 5.6. The water contact angle is an index that shows the waterproof ability of materials. A high water contact angle indicates that the material has a good waterproof property. At the same time, a slow decreasing of water contact angle within the same period shows good water resistance of the material. As shown in Figure 5.5, all the contact angles of treated space fabrics were higher than 120°. As shown in Figure 5.6, the water contact angles of the treated space fabrics decreased very slowly within 30s. Especially, the contact angles of fabric TSF A covered with polystyrene nanofibrous membrane changed little after 30s, which indicated that polystyrene nanofibrous membrane had very good water resistance. Although fabric TSF B covered with polyurethane nanofibrous membrane, had inferior waterproof property comparing with TSF A, they still gave the fabric water resistance while the untreated spacer fabrics C4-1 was wetted in 28s.

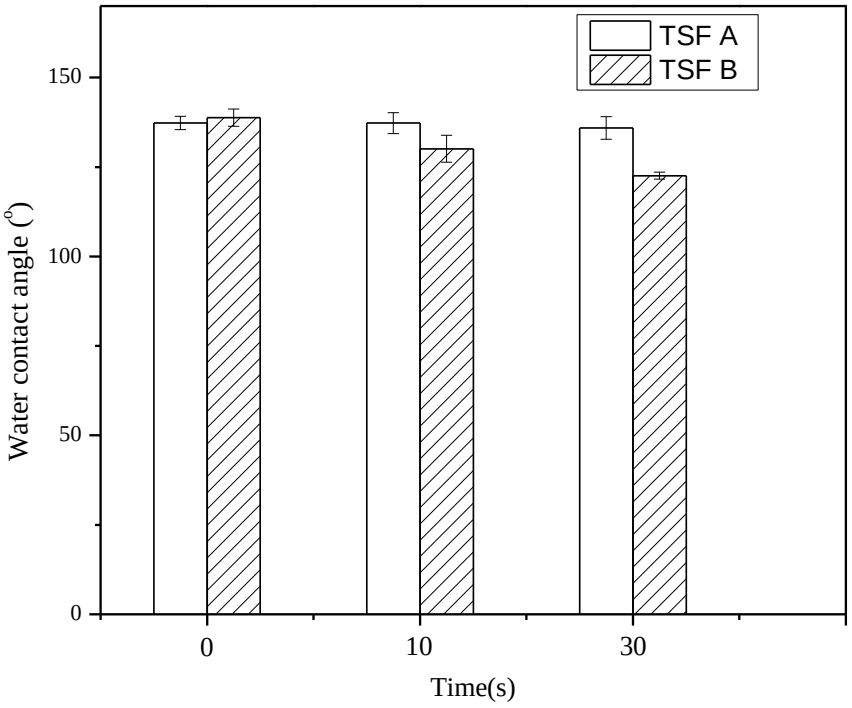


Figure 5.5 Water contact angles of treated spacer fabrics after 0s, 10s and 30s.

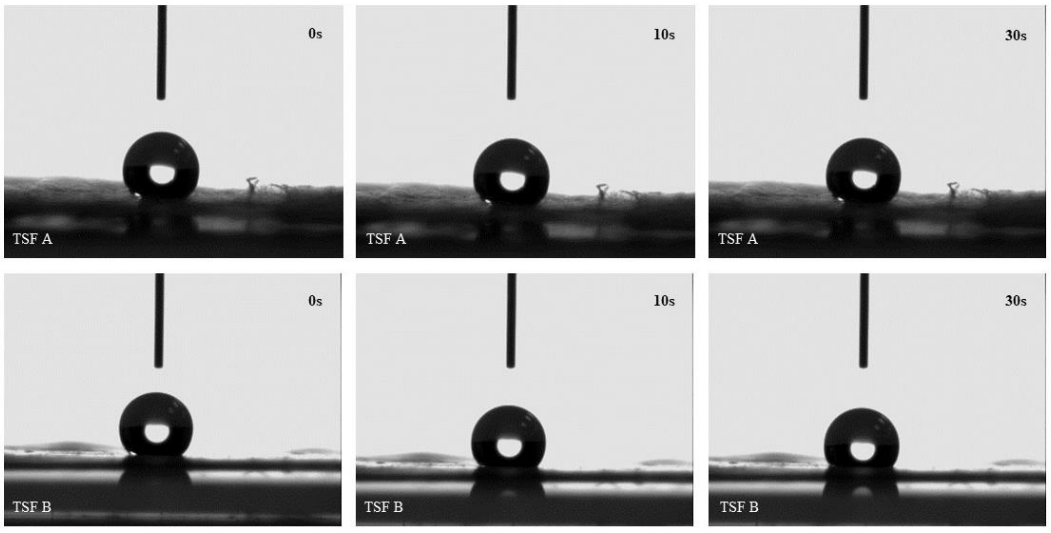


Figure 5.6 Images of water drops contacting with treated spacer fabrics after 0s, 10s and 30s.

When water dropped on the surface of treated spacer fabric, the water firstly contacted with the electrospun nanofibrous membrane. As this membrane was continuously covered on the surface of spacer fabric (as shown in Figure 5.2), the water contact angle was mainly determined by the membrane. Surface energy and surface roughness are the dominant factors for water resistance [111]. Since both the polystyrene and polyurethane membranes were obtained by electrospinning, their morphology was nanofibers, which means that their surface roughness was similar. Therefore, the main reason for polystyrene membrane had better water resistance than polyurethane membrane was that the surface energy of polystyrene membrane is lower than polyurethane membrane, which is determined by the chemical groups. According to the chemical formula shown in Figure 5.3, polystyrene has a benzene ring in its structure, whereas polyurethane has no benzene ring but carbamate instead. These different chemical groups lead to the difference of water contact angles between polystyrene and polyurethane electrospun nanofibrous membranes. The spacer yarns slightly affected the water resistance, as the tuck loops appearing on the spacer fabric surface could influence the uniformity of membranes.

5.3.1.3 Air permeability

Since the electrospun nanofibrous membrane could reduce permeability of spacer fabric, the air permeability was tested and the results are shown in Figure 5.7. The air

permeability of untreated spacer fabric C4-1 was 25 ml/s/cm^2 at 100Pa. The air permeability of TSF A (C4-1 covered with polystyrene) was higher than that of TSF B (C4-1 covered with polyurethane). This indicates that air permeability of polystyrene electrospun nanofibrous membrane was better than that of polyurethane electrospun nanofibrous membrane. As shown in the SEM images (Figure 5.4), the polyurethane electrospun nanofibrous membrane was denser than polystyrene electrospun nanofibrous membrane, which caused the lower air permeability.

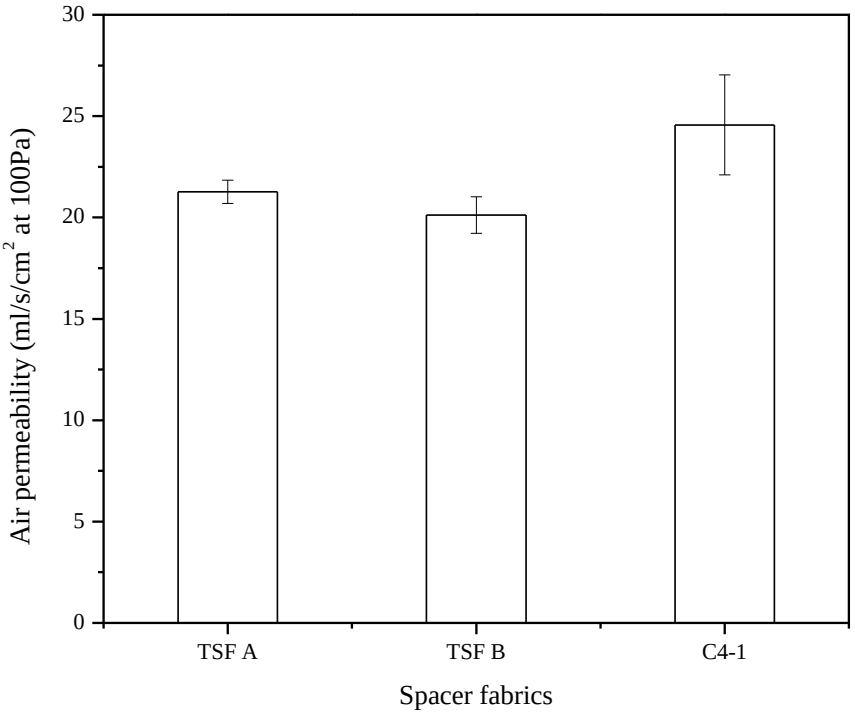


Figure 5.7 Air permeability of spacer fabrics.

5.3.2 Treatment with fluorocarbons

In order to show the actual effect, pictures were taken while spacer fabric contacting with water. Figure 5.8 displays the top layer of treated and untreated fabrics after contacting with colored water (Methylene blue solution) for 1 min. The untreated fabric was completely wetted after 1 min. For the treated spacer fabrics, the water drops could not pass through the water resistant surface and then wet the fabric. The water drops could even roll on the slanting treated surface, indicating that the water resistance of the treated fabric was very good. Figure 5.9 presents the untreated bottom layer contacted with water and the treated top layer after absorbing. Colored water was firstly dropped on the bottom layer of spacer fabrics. After the water drops were absorbed, the outer surfaces were observed. It can be seen that the top layer of untreated fabric was apparently wetted by blue water, while the treated fabric surface was scarcely wetted. This revealed the advantage in preventing exudate leakage when applying spacer fabric as a wound dressing.

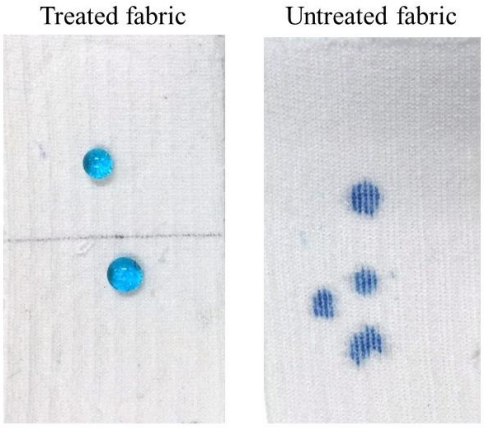


Figure 5.8 Pictures of top layer of spacer fabric contacting with water for 1 min.

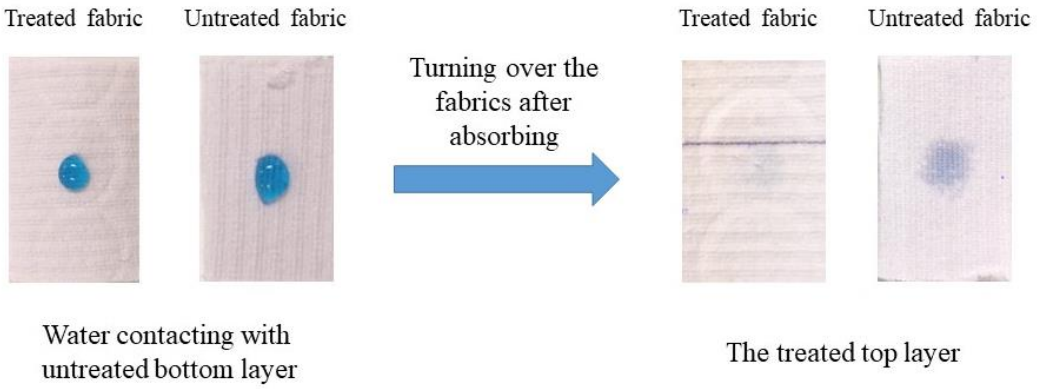


Figure 5.9 Pictures of wetted spacer fabrics.

5.3.2.1Curing time

Five curing time (3min, 5min, 10min, 15min, 20min) was used to analyze the effect of curing time on the water resistance and air permeability. In this section, the curing temperature of 130 ºC and solution concentration of 5% were applied. As discussed in the property evaluation of spacer fabric in Chapter 4, the untreated spacer fabrics C4-1 was wetted in 28s, and the air permeability was 25 ml/s/cm^2 at 100Pa. As shown in Figure 5.10, the water resistance was greatly improved for all the spacer fabrics. Contact angles of all spacer fabrics gradually decreased after water drops contacting with fabrics. The water contacting angle increased with the extension of curing time of 0 ~ 10 min. By contrast, the water contact angle diminished with the increase of curing time when it was longer than 10 min. From Figure 5.11, the air permeability of all spacer fabrics decreased after treatment. It declined from 21.9 ml/s/cm^2 to 15.6

ml/s/cm^2 at 100 Pa, while the curing time increased from 3 min to 10 min. After the 10 min, the curve shows a slight increase of air permeable values thereafter. NUVA water resistant agent was a C6-based fluorochemical and polymerization occurred when curing. A longer curing time was beneficial to improve the degree of the resin and the film formation. Hence, the water resistance could be enhanced and the flow path of air could be blocked. However, after 10 min curing, the longer curing time may cause thermal decomposition [169] which lead to the fall of water resistance and slightly rise of air permeability. As a result, the curing time of 10 min was selected in the following experiments.

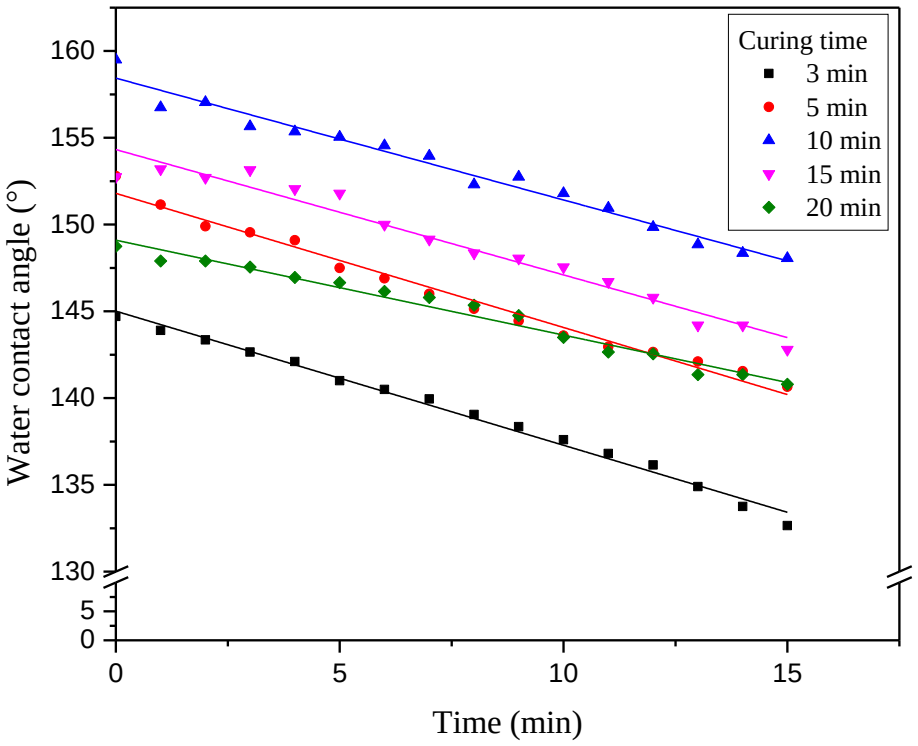


Figure 5.10 Effect of curing time on water contact angle.

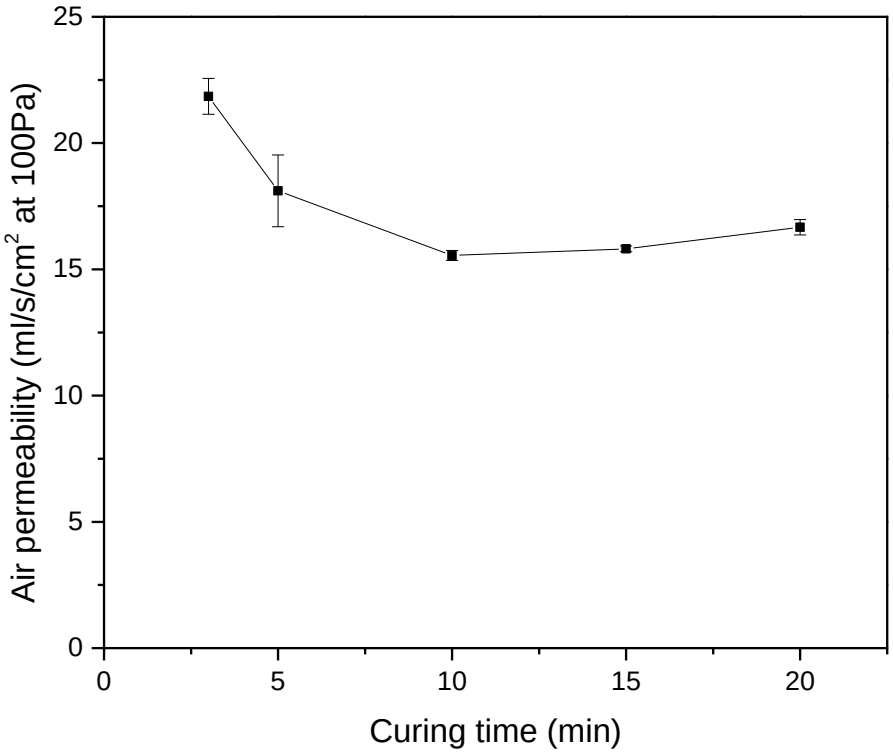


Figure 5.11 Effect of curing time on air permeability.

5.3.2.2Curing temperature

In this section, four curing temperatures (120 ºC, 130 ºC, 140 ºC, 150 ºC) were used to evaluate their effects on the water resistance and air permeability. As selected above, the curing time was 10 min and the solution concentration was 5%. Figure 5.12 presents the effect of curing temperature on water contact angle. The water contact angle of spacer fabrics cured at 120 ºC was the lowest, and that of fabrics cured at 130 ºC was the highest. The water contact angle of fabrics cured at 140 ºC was higher than

that of fabrics cured at 150 ºC, both of which were in the middle. From Figure 5.13, the air permeability descended with the increase of curing temperature. The fluorocarbon could hardly form a satisfactory degree of polymerization in low temperature, so the water resistance was poor. A higher curing temperature helped the polymerization of fluorochemical emulsion in a shorter period. However, a too high curing temperature had adverse effects on the emulsion polymerization and film-forming capacity. Therefore, the too high curing temperature led to a decrease in water contact angle.

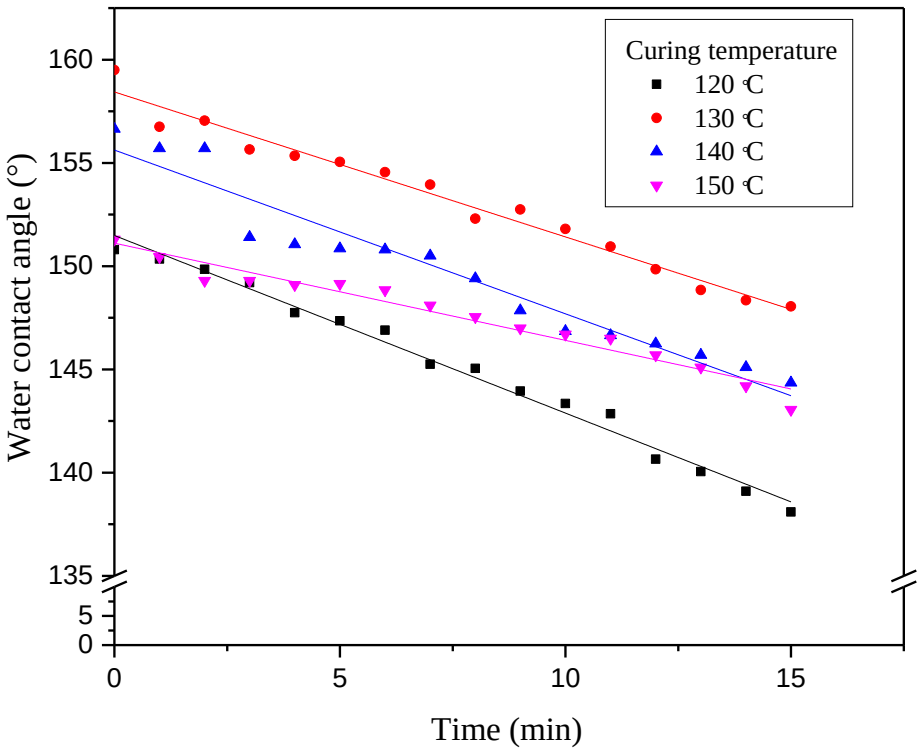


Figure 5.12 Effect of curing temperature on water contact angle.

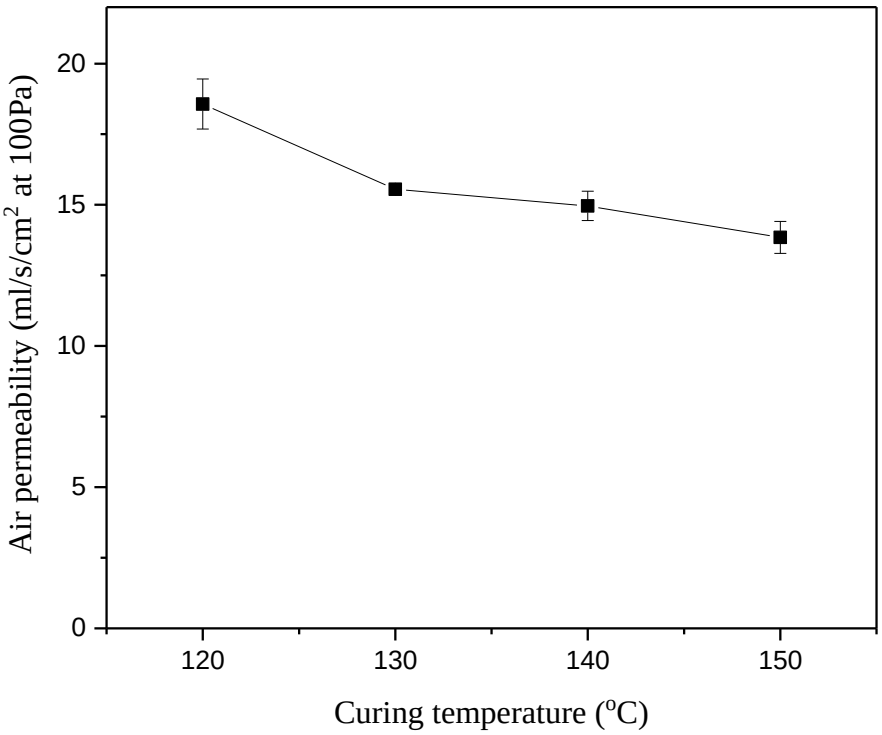


Figure 5.13 Effect of curing temperature on air permeability.

5.3.2.3Concentration

In this section, spacer fabric was treated with solution of five different concentration (2.5%, 5%, 10%, 15%, 20%) to analyze the effect of solution concentration on the water resistance and air permeability. The effect of concentration on water contact angle is illustrated in Figure 5.14. The water contact angle grew with the increase of concentration from 2.5% to 10%. Above 10%, the water contact angle fell down with the increase of concentration. Figure 5.15 shows the effect of concentration on air permeability. The fluorocarbon dosage was negatively correlated to the air

permeability. The water resistance was generally determined by the exposed atoms of the film, which means the major consideration was the need for a fluorinated carbon chain evenly distributed on the textile [170]. As a thicker and uneven fluorocarbon polymer film could form by applying dense emulsion, the water resistance was lowered by high concentration. Naturally, the thicker film caused poorer air permeability.

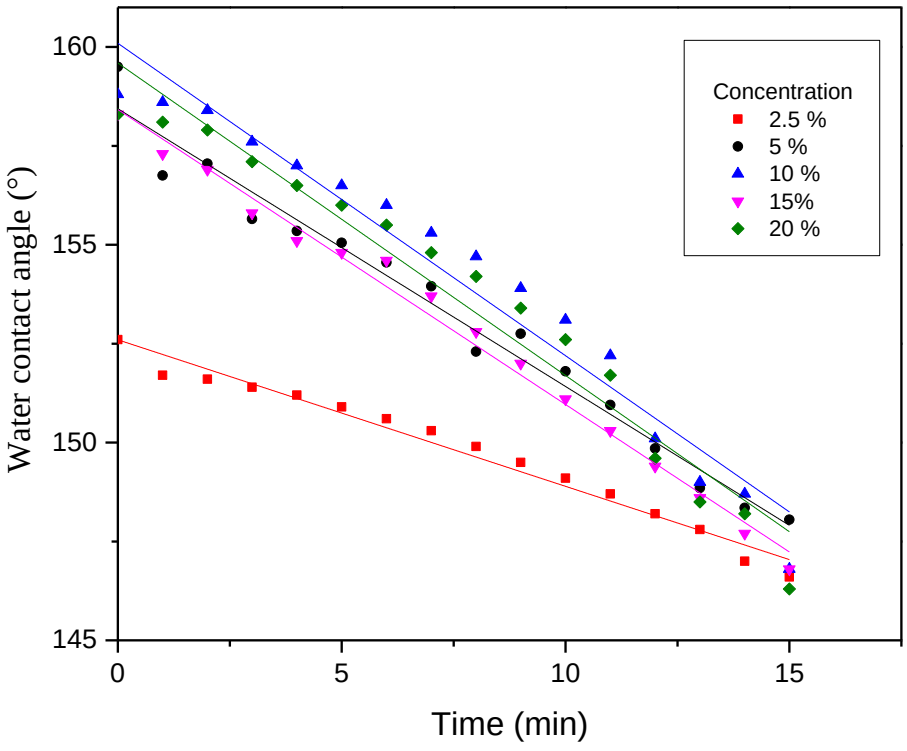


Figure 5.14 Effect of concentration on water contact angle.

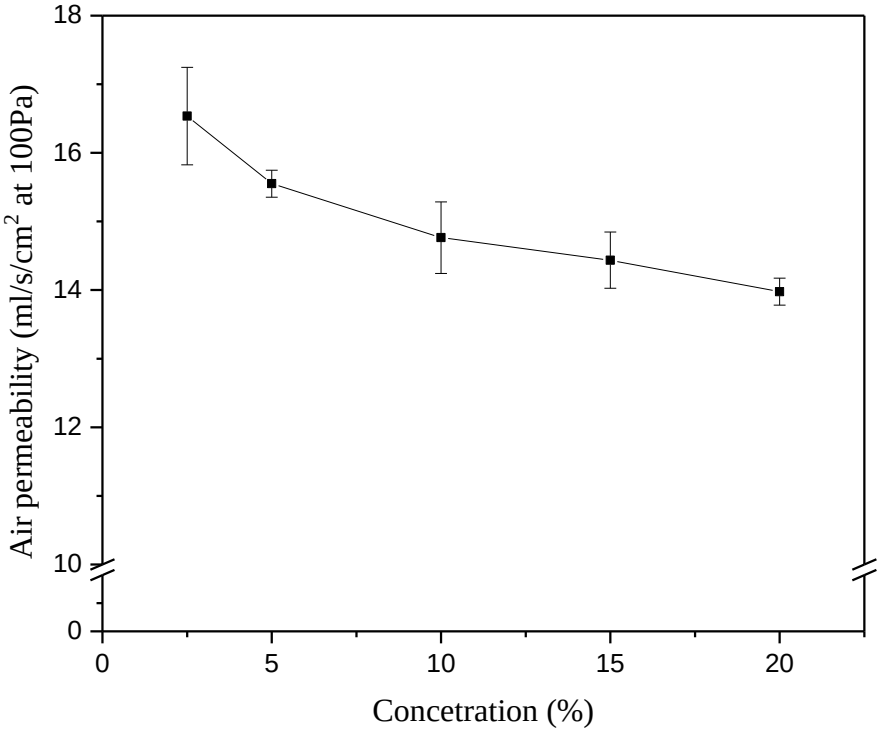


Figure 5.15 Effect of concentration on air permeability.

5.3.3 Treatment with TiO_2 nanosol

5.3.3.1 Water contact angle

As curing time had the biggest effects on water resistance and air permeability, five curing time (3 min, 5 min, 7 min, 10 min, 15 min) was carried out to test the effects. The effect of curing time on water contact angle is shown in Figure 5.16. Initially, the water contact angles of all the TiO_2 nanosol treated fabrics were higher than 145º, which indicated that their water resistance was good. The water contact angle of treated spacer fabric decreased slowly. The high water contact angle of TiO_2 nanosol

was attributed to the low surface energy of TiO_2 and the surface roughness brought by TiO_2 nanoparticles [171, 172]. The hydrophobicity of TiO_2 was affected by the duration of high temperature treatment. The water contact angles decreased with the increase of curing time, and spacer fabrics cured for 3 min had the highest water contact angles.

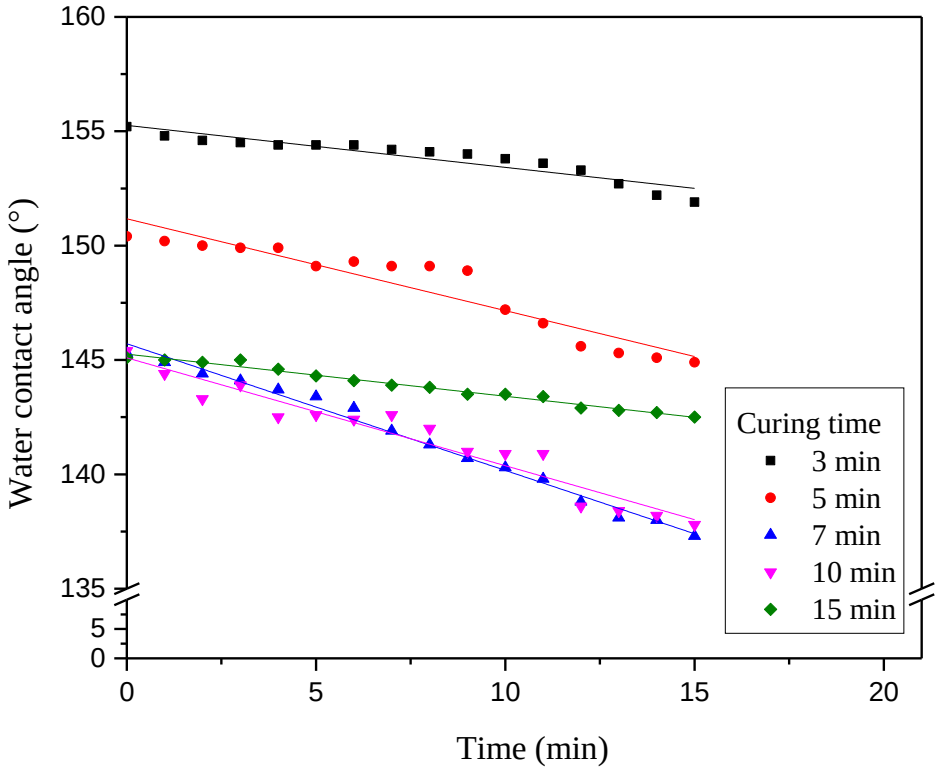


Figure 5.16 Effect of curing time on water contact angle.

5.3.3.2 Air permeability

Figure 5.17 shows the effect of curing time on air permeability. All the treated spacer fabrics had lower air permeability than untreated spacer fabric (around 25 ml/s/cm^2 at 100Pa). The covering of TiO_2 nanoparticles on the surface of spacer fabrics decreased the air permeability. The air permeability slightly increased with the curing time. The trend was counter to the change of water contact angles. After treated with TiO_2, the spacer fabrics with high water contact angles had lower air permeability. However, the change in air permeability caused by curing time was not too big. As the spacer fabric cured for 3 min had the highest water contact angle, this curing time was selected.

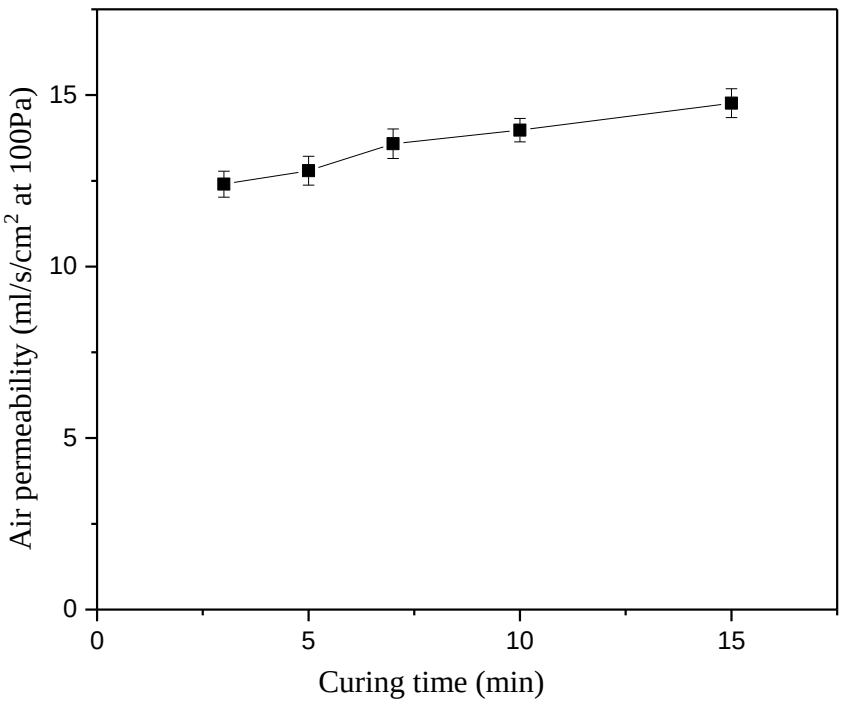


Figure 5.17 Effect of curing time on air permeability.

5.4 Conclusion

As wound dressing should keep contaminated fluid and harmful substance away from the wound, water resistant treatments were carried out on spacer fabric surface. The aims of these methods were not only to make the spacer fabric water resistant, but also to keep the good air permeability of spacer fabric. In this regard, three kinds of water resistant treatments were applied including treatment with electrospun nanofibrous polyurethane or polystyrene membrane, treatment with fluorocarbons agent NUVA N2114 and treatment with TiO_2 nanosol. The treated spacer fabrics were evaluated by the water contact angle test and air permeability test. According to the experimental results and analyses, the following conclusions can be drawn.

a) Spacer fabric treated with polystyrene electrospun nanofibrous membrane had higher water contacting angle and better air permeability, while spacer fabric treated with polyurethane electrospun nanofibrous membrane could form a better film and had better adhesion on the fabric surface. Their water contact angles were higher than 130^{o}, and their air permeability was higher than 20 ml/s/cm^2. The spacer fabric C4-1 treated with polyurethane electrospun nanofibrous membrane is named as spacer-fabric-based dressing 1 (SFBD 1).

b) The water resistance of spacer fabric treated with the fluorocarbons agent NUVA N2114 was high. The processing conditions were optimized as spraying the solution of concentration 10% on the spacer fabric top layer and then cure the fabric at 130 ^{o}C for 10min. The treated spacer fabrics not only have good water resistance, but also

could prevent leakage of exudate. The water contact angles were higher than 145º, and the air permeability was higher than 13 ml/s/cm^2. The spacer fabric C4-1 treated with fluorocarbon NUVA N2114 in optimal condition was named as spacer-fabric-based dressing 2 (SFBD 2).

c) The water resistant effect of TiO_2 nanosol treatment was significant. The optimal finishing process was to spray the TiO_2 nanosol of concentration 1% on the spacer fabric surface and then cure the fabric at 160 ºC for 3 min. The water contact angles were higher than 145º, and the air permeability was higher than 12.5 ml/s/cm^2. The spacer fabric C4-1 treated with TiO_2 nanosol in optimal process was named as spacer-fabric-based dressing 3 (SFBD 3).

In conclusion, spacer fabrics treated with fluorocarbons and TiO_2 nanosol had higher water resistance than spacer fabric treated with electrospun nanofibrous membrane. However, the air permeability of the later one was better than that of the former ones. In the next chapter, spacer-fabric-based dressings (SFBD 1, SFBD 2 and SFBD 3) will be compared with commercial dressings to evaluate their potential to be used as absorbent wound dressing.

Chapter 6 Comparison with commercial absorbent wound dressings

6.1 Introduction

In order to confirm the performance of the spacer fabric used as wound dressing, the most commonly used absorbent dressing should be selected as the representative dressing to compare with spacer-fabric-based dressing. Foam dressing is a popular type of advanced wound dressings on the market which could absorb and retain fluid to maintain an ideal moist environment for wound. Allevyn non-adhesive has withstood the test of time and continues to be an essential for patients and clinicians all over the world. Allevyn non-adhesive foam dressing is made from hydrocellular polyurethane foam. Its absorption is high and could effectively manage fluid to create a moist wound environment. Other absorbent dressings, such as the hydro-active polyurethane matrix and hydrophilic polyurethane matrix are not readily available on the market. CUTINOVA Hydro is a kind of hydro-selective polyurethane gel matrix. However, Allevyn non-adhesive foam dressing has been proved having better absorbency than the hydro-active polyurethane gel matrix CUTINOVA Hydro [28]. So Allevyn non-adhesive foam dressing from Smith & Nephew was selected to compare with spacer-fabric-based dressing. Another often used foam dressing, Biatain non-adhesive foam dressing from Coloplast was also used as a compare. Alginate

wound dressings are made of soft non-woven fibers derived from seaweed. The dressing turns into a gelatinous mass as it absorbs exudate by exchanging sodium ions with calcium ions from the wound. It has been applied on exuding wounds to promote wound healing, while the formed gel avoids dressing fibers contaminating the wound. An alginate dressing from Smith & Nephew was also used in this chapter to compare with spacer-fabric-based dressing.

This chapter regards the spacer-fabric-based dressing as a whole, and compares them with the commercial absorbent dressings with highest performances. Most of the tests were carried out based on the standard test method for primary wound dressings BS EN 13726. In the comparison, a series of tests including the wettability, absorbency, moisture transmission, air permeability, extensibility and water contact angle tests were conducted. The wound contact surface of spacer fabric should be immediately wetted while contacting with the wound bed. This is important for wound care that dressings should absorb exudates quickly to avoid fluid collecting around the wound and adjacent intact skin. A high absorbency gives dressing high capability of containing exudates. The moisture transmission represents the ability to keep a moist environment for wound and avoid maceration, which is one of the most important things for an absorbent dressing. The extensibility shows the comfort of a dressing and the possibility to fit a certain part of body. Both the spacer-fabric-based dressings and the commercial dressings were evaluated by all the property tests.

6.2 Experimental

6.2.1 Materials

The comparison was conducted between spacer-fabric-based dressings and three types of commercial dressings for heavily exudate wounds. Untreated spacer fabric C4-1 and spacer-fabric-based dressings treated with the electrospun nanofibrous membrane (SFBD 1), fluorocarbons (SFBD 2) and TiO_2 nanosol (SFBD 3) were used. Commercial dressings included Foam A, Foam B and Alginate. The details and images of these commercial dressings are shown in Table 6.1 and Figure 6.1. Foam A was a soft and conformable hydrophilic polyurethane foam dressing that could effectively absorb and retain wound exudate. It ensures an optimal moisture balance for the healing of exuding wounds. Foam B was a dressing made of hydrocellular foam. It could absorb and retain enough fluid to maintain an ideal moist wound environment and could transpire enough fluid to keep the dressing comfortable and conformable. Alginate dressing contained salts of alginic acids which could interact with physiological fluids to form a gel. All the dressings were non-adhesive, this is, there was no adhesive film on their surface to make the comparison under the same condition. As can be seen from Table 6.1, the foam dressings were thicker than all the spacer-fabric-based dressings, but the alginate dressing was thinner and lighter than all the spacer-fabric-based dressings. Thick dressings offer good absorption and good protection for wound, but too thick dressings may cause patients uncomfortable.

Table 6.1 Details of the commercial wound dressings.

Type	Base material	Product name & Brand	Size	Areal mass (g/m^2)	Thickness (mm)
Foam A	Hydrophilic polyurethane foam	Biatain non-adhesive foam dressing from Coloplast	10 cm × 10 cm	754 (± 23.1)	4.65 (± 0.06)
Foam B	Hydrocellular polyurethane foam	Allevyn non-adhesive foam dressing from Smith & Nephew	10 cm × 10 cm	680 (± 14.2)	5.70 (± 0.05)
Alginate	Calcium alginate	Algisite from Smith & Nephew	10 cm × 10 cm	136 (± 6.5)	2.28 (± 0.02)

Note: Standard deviations are given in parentheses.

Figure 6.1 Images of surfaces and cross-sections of commercial dressings.

6.2.2 Property evaluation

The following performance indicators were used for the comparisons between the spacer-fabric-based dressings and commercial products, including wettability, absorbency, water contact angle, air permeability and fluid handling capacity of primary dressings. The water resistant treatments mainly affect the water resistance and permeability of air and water vapor, the wettability, so the absorbency and mechanical properties were compared between untreated spacer fabric C4-1 and commercial dressings. The other properties were compared between the spacer-fabric-based dressings (SFBD 1, SFBD 2 and SFBD 3) and commercial dressings. All the samples were conditioned in a standard atmosphere at 65 ± 2 % relative humidity (RH) and 20 ± 2 ºC for one week before use.

6.2.2.1 Wettability test

As the wound contact layer should be wetted quickly when contacting with the wound to accelerate the exudate absorption and avoid maceration, wettability tests were carried out on the wound contact layer. Wetting time of samples was measured according to the standard AATCC 79 method, which was detailed in section 3.4.1.

6.2.2.2 Absorbency of liquid containing Na^+ and Ca^{2+} ions test

For the comparison of dressings, the liquid containing Na^+ and Ca^{2+} ions was used to replace the distilled water in absorbency test to simulate the wound exudates according to BS EN 13726-1 - Test Method for Primary Wound Dressings. The test solution, which was prepared by dissolving 8.298 g/L sodium chloride and 0.368 g/L calcium chloride (AR grade, purchased from Oriental Chemicals & Lab. Supplies Ltd) in distilled water, had an ionic composition comparable to human serum or wound exudate. A 5 cm × 5 cm ($25cm^2$) sample was first put in a warmed solution (37 ºC) having 40 times of the mass of dressing, and then transferred to an oven to stand for 30 min at 37 ºC and finally drained for 30s. Five specimens were tested for each type of fabrics and dressings. The absorbency was calculated according to Equation 6.1.

$$\text{Absorbency } (g/100cm^2) = (W_1 - W_0)/25 \times 100 \qquad \text{Equation 6.1}$$

Where W_0 is the mass of dry sample (g); W_1 is the mass of sample after absorbing (g).

6.2.2.3 Extensibility and elastic recovery property test

The tensile tests for extensibility and elastic recovery property were carried out on Instron 4411 tester. The weft and warp directions of spacer fabrics were tested. For commercial dressings, the horizontal and vertical directions of alginate dressing were

tested, and there was no difference between directions of foam dressings. Extensibility was tested according to BS EN 13726-4 - Test Method for Primary Wound Dressings, where 25 mm × 100 mm specimen (clamping length 80 mm) was extended by 20% for 60 seconds and relaxed for 300 seconds using an extension rate of 300 mm/min. The maximum load (ML) both for weft and warp directions of spacer fabrics, horizontal and vertical directions of alginate as well as foam dressings were recorded and the extensibility was calculated using Equation 6.2:

$$\text{Extensibility (N/cm)} = ML/2.5 \qquad \text{Equation 6.2}$$

Where ML is the maximum load when the sample is stretched to 20% (N).

To test elastic recovery property, the cycling tensile test at a constant elongation was carried out according to Chinese Standard FZ/T 01034 with the following test conditions: sample size 50 mm × 100 mm, 20% elongation, 50 mm clamping length, the jaw speed of 100mm/min and repeating 50 cycles. Three specimens from different sites of each sample were tested. As there is a big difference between the course direction and wale direction of spacer fabrics, the tests in both directions were carried out. The extended length was recorded and the rate of elastic recovery for each cycle was calculated according to Equation 6.3.

$$\text{Rate of elastic recovery (\%)} = (L_1-L_0)/L_0 \qquad \text{Equation 6.3}$$

Where L_0 is the clamping length (mm); L_1 is the length of sample after being extended when the load is 0 (mm).

6.2.2.4 Water contact angle test

Water contact angle tests were detailed in section 5.2.4.1. Pictures of water drops at 0s were captured and the water contact angles were tested. Five specimens were used for each type of samples.

6.2.2.5 Air permeability test

The air permeability testing method of wound dressings was the same as described in section 3.4.4 in accordance with ASTM D737. The wound contact layer faces down to encounter the flow of air at the first place. The capacity of the SDL M021S air permeability tester for the maximum value and minimum value are 78.040 ml/s/cm^2 and 0.020 ml/s/cm^2 at 100Pa, respectively.

6.2.2.6 Fluid handling capacity test

The fluid handling capacity was evaluated according to the test methods for primary wound dressings BS EN 13726-1. Moisture vapor transmission rate (MVTR) was tested when water contacting with the dressings. This method simulated the process when an absorbent dressing applying to an exuding wound. Add 20 ml water in the test cylinder with an internal diameter of 63 mm (cross-sectional area 31.16 cm^2). Cut circular samples suitable to be fixed over the test apparatus to prevent leakage. After fixing the sample on the cylinder, the assembled cylinder was weighed (W_1). Invert the cylinder to allow water to contact with the dressing. Place the assembled cylinder in the oven at 37 ^oC and below 20% RH. After 24h, reweigh the cylinder (W_2). The MVTR was calculated as Equation 6.4.

$$MVTR\ (g/(24h*m^2)) = (W_1-W_2)/A \qquad \text{Equation 6.4}$$

$$A = \pi d^2/4\ (d=0.063m)$$

Where W_1 and W_2 are the masses of the cylinder with water and fabric sample at the beginning and after 24h of the test (g); A is the evaporation area (m^2); and d is the inner diameter of the cylinder (m).

6.3 Results and discussion

6.3.1 Wettability

Wettability is the ability of a material to absorb liquid into its body. A shorter wetting time indicates that fluid can be absorbed into dressing faster, and therefore, the material has better wettability. The wetting time of the spacer fabrics and commercial dressings are shown in Figure 6.2. It can be seen that Foam B required the longest time, more than 60 seconds to be wetted, which means Foam B performed the worst in wettability. Although Foam B was made from hydrocellular polyurethane foam, there is a non-adherent film on its wound contact layer (Table 6.1). The non-adherent film lowered the adherence and reduced the pain while removing the dressing, but it also blocked liquid to entry into the dressing directly. Foam A was also made of polyurethane foam, but its wetting time was much shorter than Foam B, because no film covers the wound contact layer of Foam A. The wetting time of Alginate was the shortest due to its main ingredient calcium alginate is a type of salts. Consequently, water could spread on its surface quickly and lose its reflectivity directly once contacted.

The wetting time of the spacer fabric mainly depends on the type of spacer yarns. As shown in Figure 4.3, the loop heads of cotton spacer yarns formed some absorbent dots on the hydrophobic surface, which could contact with exudates directly and

quickly guide the liquid into the middle layer. The wettability of spacer fabric was slower than Foam A, but much faster than that of Foam B. A better wettability is important for wound care while exudate comes out, and the dressing should absorb it quickly to avoid fluid collecting around the wound and adjacent intact skin. After being wetted, the absorbent yarns of the spacer fabric could begin to absorb great amounts of exudates.

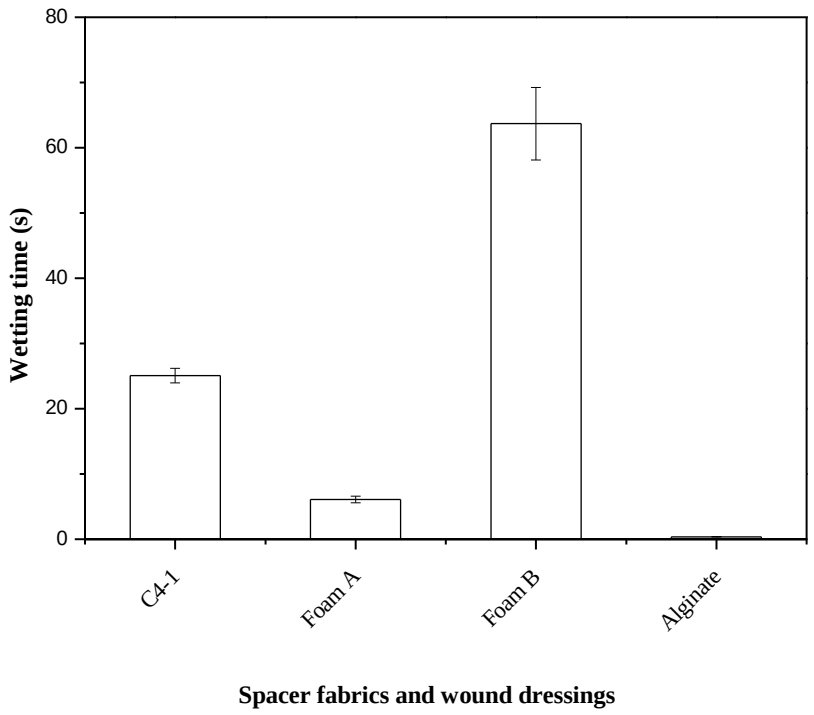


Figure 6.2 Wetting time of spacer fabrics and wound dressings.

6.3.2 Absorbency of liquid containing Na^+ and Ca^{2+} ions

As the wound dressing was evaluated as a whole, the absorbency was calculated by per 100 cm^2 area. The absorbency of liquid containing Na^+ and Ca^{2+} ions of spacer fabrics and dressings is presented in Figure 6.3. It can be seen that Alginate had the lowest absorbency, which was 19.66 g liquid absorbed by 100 cm^2 of material. The main reason is that the thickness of the Alginate wound dressing was only 2.28 mm, much thinner than others (the thickness of foams was higher than 4.65 mm and that of spacer fabrics was higher than 3.25 mm). It is therefore when calculating the areal absorbency, the value of Alginate dressing was very low. However, Alginate dressing could react with liquid by exchanging sodium ions with calcium ions to create a fibrous gel, which is helpful for absorbing the ionic liquid.

Foam A absorbed 74.8 g liquid per 100 cm^2, while Foam B just absorbed over 30 g. Both Foam A and Foam B were made of hydrophilic polyurethane foams. Hydrophilic polyurethane foam was produced by grafting hydrophilic compounds on the polyurethane surface. These compounds are macromolecules with unsaturated double bonds such as acrylic acid, acrylamide and so on. The hydrophilic groups on the polymer chains would form hydrogen bonds with water molecules. Foams swell when absorbing water and store water in the material. In the absorbency test, Foam A obviously swelled more than Foam B, so that the polyurethane matrix of Foam A could

contain more liquid inside its body. In addition, the absorbency of Foam B was reduced by the non-adherent film on its wound contact layer.

As for the spacer fabric, its absorbency was better than that of Foam B and Alginate. A large amount of liquid absorption extends the dressing period and reduces the frequency of dressing change. Furthermore, all exudates emitted from the wound should be entirely absorbed by the dressing. The liquid retention sustains a moist environment for wound healing. Consequently, the spacer fabric was competent to be used as absorbent dressing for exuding wound.

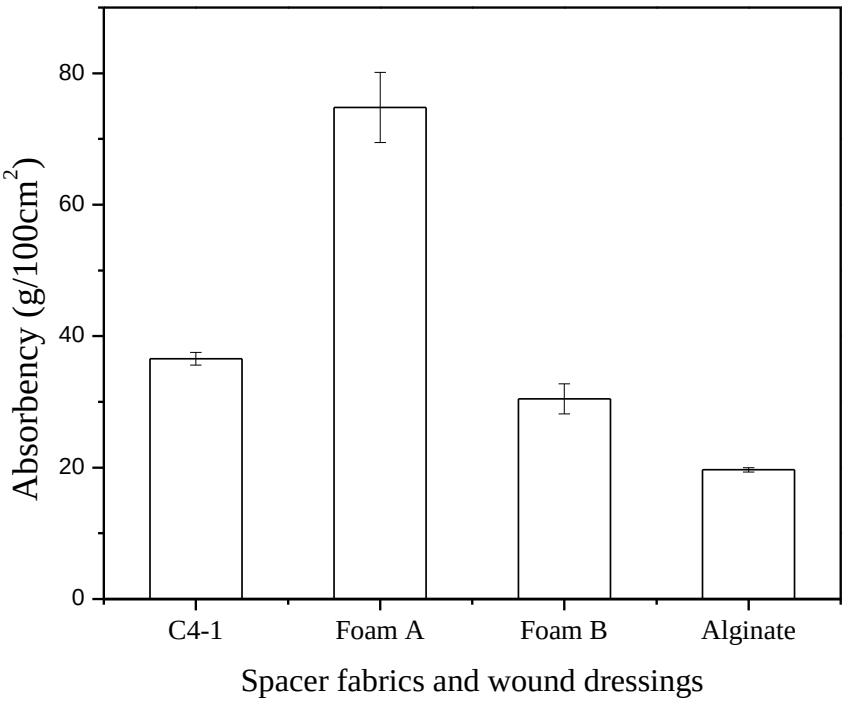


Figure 6.3 Absorbency of liquid containing Na^+ and Ca^{2+} ions of spacer fabrics and wound dressings.

6.3.3 Extensibility and elastic recovery property

To assess the ability to adapt to the shape and movement of the body, the extensibility for each spacer fabric and dressing was measured and the results are shown in Figure 6.4. A high value of extensibility means that a high force is required to deform a material for a given extension. The higher the value is, the poor the extensibility is. From Figure 6.4, it can be seen that the extensibility of foam dressings was poorer than that of spacer fabrics in both weft and warp directions. As for Alginate, its extensibilities in two perpendicular directions were quite different. This means that it had different deformations in different directions. Therefore, the alginate dressing was not suitable for using in movement regions of the body.

As wound dressing contacts with human skins during use, they should be comfortable and conformable. When a dressing is applied to a region of movement of the human body, for example over a joint, it should provide sufficient freedom to the joint to move. A dressing which is easily extended and can return closely to its original length after extension will be more comfortable for the patient to wear. Spacer fabric was suitable for applying as wound dressing because of its advantageous extensibility.

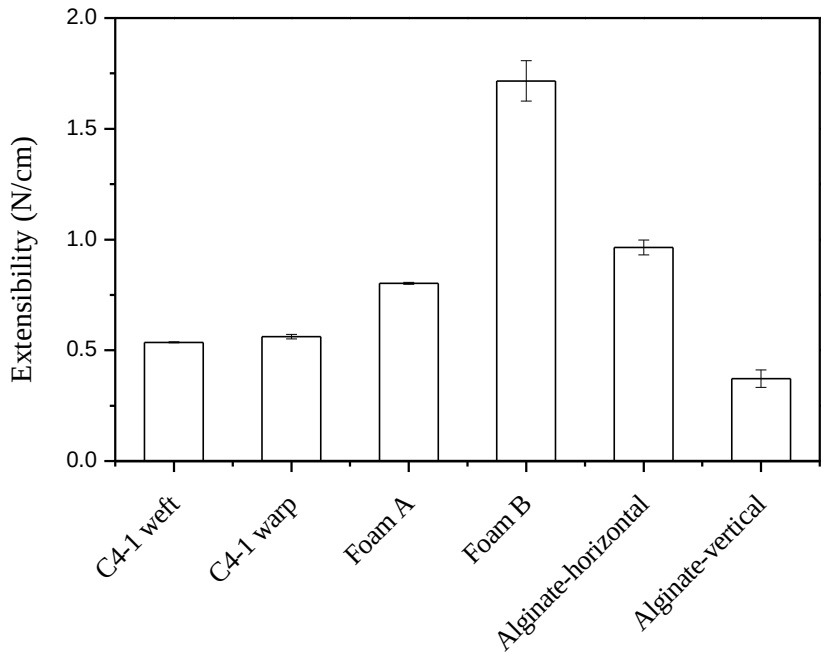


Figure 6.4 Extensibility of spacer fabrics and wound dressings.

In order to simulate the wearing condition of spacer fabrics and dressings, the cycle tensile tests were carried out and the results are displayed in Figure 6.5. As the breaking strength of Alginate was small and it could not complete 50 cycles of elastic recovery test, data of its elastic recovery is not shown in this figure. It can be seen that the elastic recovery property of Foam A was better than others, and that of treated spacer fabric C4-1 in the weft direction was the poorest. The high temperature in the treatment reduced the elastic recovery of spandex used in the surface layer of spacer fabric, so the rate of elastic recovery of treated spacer fabric was low. The largest deformation happened in the first cycle for all the spacer fabrics and wound dressings.

After the first cycle, the rate of elastic recovery just slightly decreased for the rest 49 cycles.

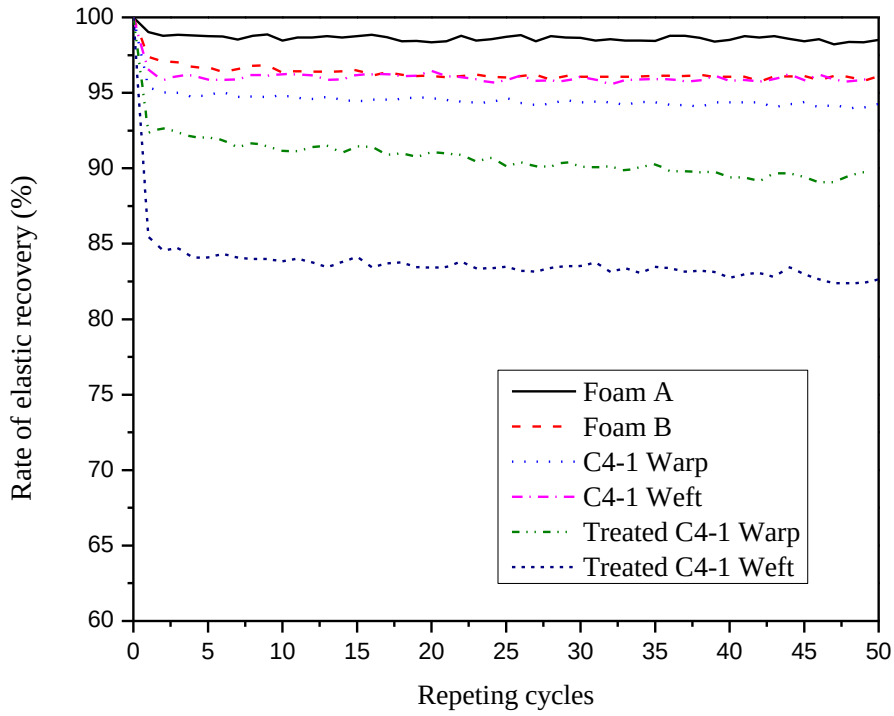


Figure 6.5 Elastic recovery property of spacer fabrics and wound dressings. (Treated C4-1 was finished with antimicrobial treatment and TiO_2 nanosol water resistant treatment)

The high elastic recovery rate represents that the sample tends to keep the original size and shape after being stretched. It is important for patients who would like to use wound dressings on their joints or other moving places. A wound dressing with low elastic recovery rate easily deforms, thus, it could hardly fit the patients' body for a

long time. The rate of elastic recovery of treated spacer fabric was around 85%, much better than the broken alginate dressing. This indicates that spacer fabric was potential to be used as wound dressings in the light of their mechanical properties.

6.3.4 Water contact angle

The water contact angle test was carried out between the spacer-fabric-based dressings processed with water resistant treatments (SFBD 1, SFBD 2 and SFBD 3) and commercial wound dressings. The water contact angles of spacer fabrics and wound dressings and the pictures of water drops on their surfaces are presented in Figure 6.6. A high water contact angle represents good water resistance. It is clear that all the spacer-fabric-based dressings (SFBD 1, SFBD 2 and SFBD 3) had significantly higher water contact angles than the commercial dressings. While the contact angles of Foam A and Foam B were less than 100°, those of all spacer-fabric-based dressings were high than 130°. Alginate dressing was absorbent without hydrophobic surface, and therefore the drop of water spread out immediately.

For the spacer-fabric-based dressings, SFBD 2 had the highest water contact angle. The SFBD 2 was treated with fluorochemicals, so its superhydrophobic property is better than fabrics treated with other repellents. The water contact angle of SFBD 3 treated with TiO_2 was just below the best one. The lotus effect of TiO_2-coated surface

imparted good water resistance to spacer fabrics. As the spacer-fabric-based dressings had better water resistance than the commercial dressings, they could protect wounds better from contaminated fluids or even infection.

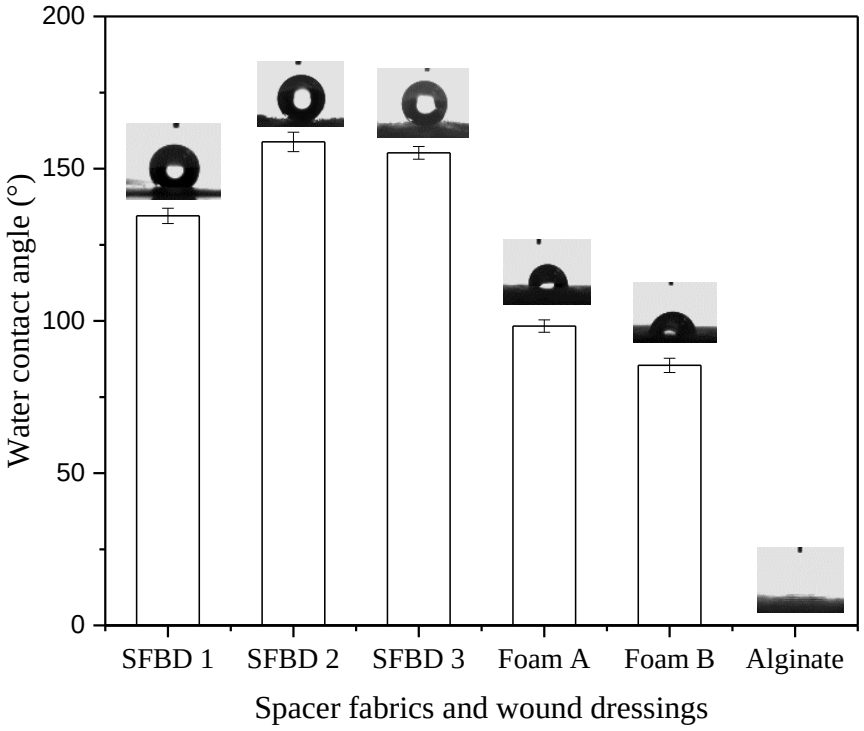


Figure 6.6 Water contact angles of spacer fabrics and wound dressings.

6.3.5 Air permeability

The air permeability test was carried out for untreated spacer fabric C4-1, the spacer-fabric-based dressings processed with water resistant treatments (SFBD 1, SFBD 2

and SFBD 3) and commercial wound dressings. The testing results of air permeability are presented in Table 6.2. It can be seen that the air permeability values of Foam A and Foam B were smaller than 0.020 ml/s/cm^2 at 100Pa, exceeding the minimum value that SDL M021S tester could measure. This implicates that the air permeability of Foam A and Foam B was very poor. As shown in Figure 6.7(a), the foam dressings were quite thick. They were made from dense polyurethane foams with a few small irregular pores inside. It was difficult for air to pass through the polyurethane matrix. In addition, the non-adherent film on the surface of Foam B further reduced the air permeability. As Alginate dressing had the lowest thickness and a loose non-woven structure, its air permeability was very high, exceeding the maximum test value of the tester, which is 78.740 ml/s/cm^2 at 100Pa. However, the too high air permeability of Alginate made it a non-occlusive dressing. In this case, a secondary dressing was required, and the most commonly used secondary dressing was gauze.

Table 6.2 Air permeability of wound dressings.

Sample code	Air permeability (ml/s/cm^2 at 100Pa)
Untreated spacer fabric C4-1	24.567 (± 2.472)
SFBD 1	20.118 (± 0.906)
SFBD 2	14.764 (± 0.521)
SFBD 3	12.402 (± 0.380)
Foam A	< 0.020
Foam B	< 0.020
Alginate	> 78.740

Note: Standard deviations are given in parentheses.

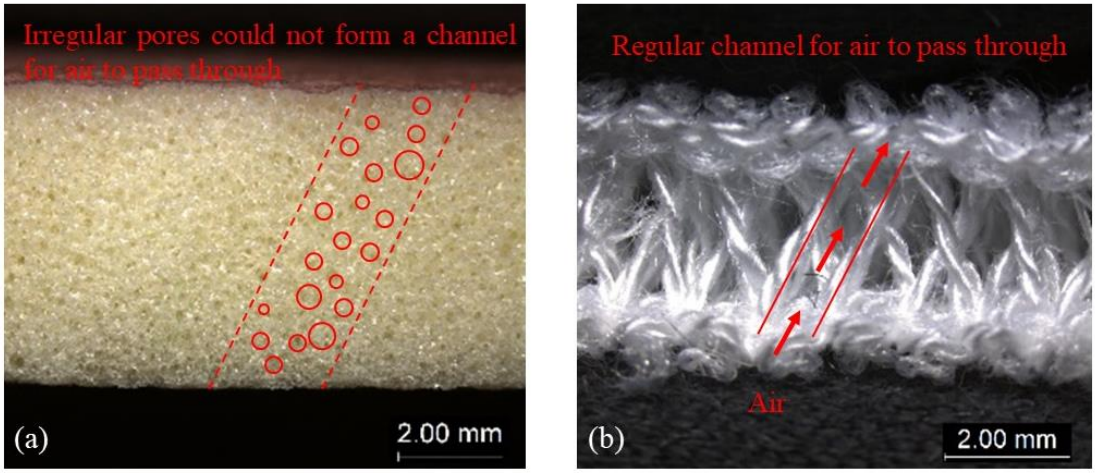


Figure 6.7 Mechanism of air resistance of (a) foam dressing and (b) spacer-fabric-based dressing.

The values of air permeability of the spacer-fabric-based dressings could be measured by the tester. They were higher than those of Foam A and Foam B, but lower than that of Alginate. The air permeability of the spacer-fabric-based dressings was much better than that of the foam dressings due to the lower thickness and density of the fabric structure. As shown in Figure 6.7, the spacer-fabric-based dressings consisted of repeating units, and these regular units generated regular channels (Figure 6.7 (b)) rather than the irregular structure of polyurethane matrix (Figure 6.7 (a)). The openings regularly arranged in a spacer fabric structure reduced air resistance and facilitated air circulation. On the contrary, the small pores irregularly arranged in a foam structure could not form smooth passages to let air free flow. The spacer-fabric-based dressings were thicker and denser than Alginate, so that air was more difficult to pass through the spacer-fabric-based dressings than Alginate.

In addition, the water resistant treatments reduced spacer fabric's air permeability. As shown in Table 6.2, untreated spacer fabric C4-1 had the highest air permeability. The air permeability of SFBD 1 was better than that of the other two treatments. The SFBD 1 was treated with the highly permeable electrospun membrane, whereas coating method was adopted in the other two treatments. The electrospinning formed a layer with nanofibers, which was similar with a non-woven structure with plenty of pores. The chemicals treated by coating tended to form continuous membrane, which lowered the air permeability.

The rate of wound healing may be reduced by the limited oxygen supply. This suggests that the wound healing may be promoted by increasing oxygen exchange. [173, 174] The permeable dressing help to increase collagen production when comparing with non-porous dressing. [175] Air exchange also improves the fibroblast proliferation, reepithelialization and poly-morphonuclear cell functions. [176, 177] In addition, as anaerobic bacteria were reported to cause the production of volatile odorous molecules [8, 178], wound dressing should permit diffusion of air to reduce wound malodor. Spacer-fabric-based dressing has a great advantage to provide adequate wound oxygenation.

However, it is hard to make a material to have good air permeability and good water resistance at the same time. Most of the wound dressing materials have good air

permeability but poor water resistance, such as Alginate and cotton gauze; or have a good waterproof but poor air permeability, such as foam dressings. The combination of spacer fabrics and permeable repellents provided a good solution to this difficult problem. The spacer-fabric-based dressings had quite good air permeability and very good waterproof. As a result, they were qualified for applying as wound dressings with good permeability.

6.3.6 Fluid handling capacity

The fluid handling capacity could be evaluated by the absorbency and moist vapor transmission of the material. Untreated spacer fabric, treated spacer fabric (SFBD 1, SFBD 2 and SFBD 3) and commercial dressings were included in this test. The moist vapor permeability was measured when water contacting with dressing, which represented in situ scenarios. The samples absorbed water, while moist vapor kept evaporating from the samples.

The MVTRs of spacer fabrics and dressings contacting with water are presented in Figure 6.8. These data provide evidence that the MVTRs of SFBD 2 and SFBD 3 were lower than that of Foam A and Foam B. This indicates that the designed spacer-fabric-based dressings had a very good capacity to create a moist environment for wounds, which was the key criteria for exuding wound dressings. As the spacer-fabric-based

dressings were obtained by treating spacer fabrics with water resistant agents, the MVTRs of the treated SFBD 1, SFBD 2 and SFBD 3 were lower than the untreated spacer fabric C4-1, which means the moisture retaining capacity was improved by the water resistant treatments. Despite alginate dressing could form a fibrous gel while contacting with water, it was non-occlusive and the leakage of water was inevitable without a secondary dressing. Thus, the MVTR of alginate dressing could not be measured using this testing method.

Another issue that deserves attention is the deformation of foam dressings after absorbing water. The foam dressings swelled after absorbing water, which are presented in Figure 6.9. As show in the pictures, the thicknesses of Foam A and Foam B were both increased. Foam A concaved towards the wound contact layer, and Foam B bulged toward the top layer. The main reason for the swell is that the hydrophilic and hydrocellular polyurethane foams combined with water and stored water inside its body, which increased their volumes. As the foams were fixed during the tests, the swelled foam could not expand towards the edges around, therefore, the deformation appeared. This deformation also could happen when the foam dressings applying on the wound, because the dressings should be fixed to cover on the wound while using. The deformed dressing would not fit with the shape of body, which lowers the moisture of wound healing environment and cause dehydration and healing delay of wound. The shape of spacer fabric and spacer-fabric-based dressings did not change

after absorbing water. The high porosity of spacer fabric gave enough space to swelling cotton yarns while absorbing water. Thus, the spacer-fabric-based dressing had no significantly deformation. Spacer-fabric-based dressing could probably reduce the negative effects on wounds caused by the shape change. As a result, the spacer fabric had an advantage in keeping a moist environment for wound and avoid maceration, which is one of the most important requirements for an absorbent dressing.

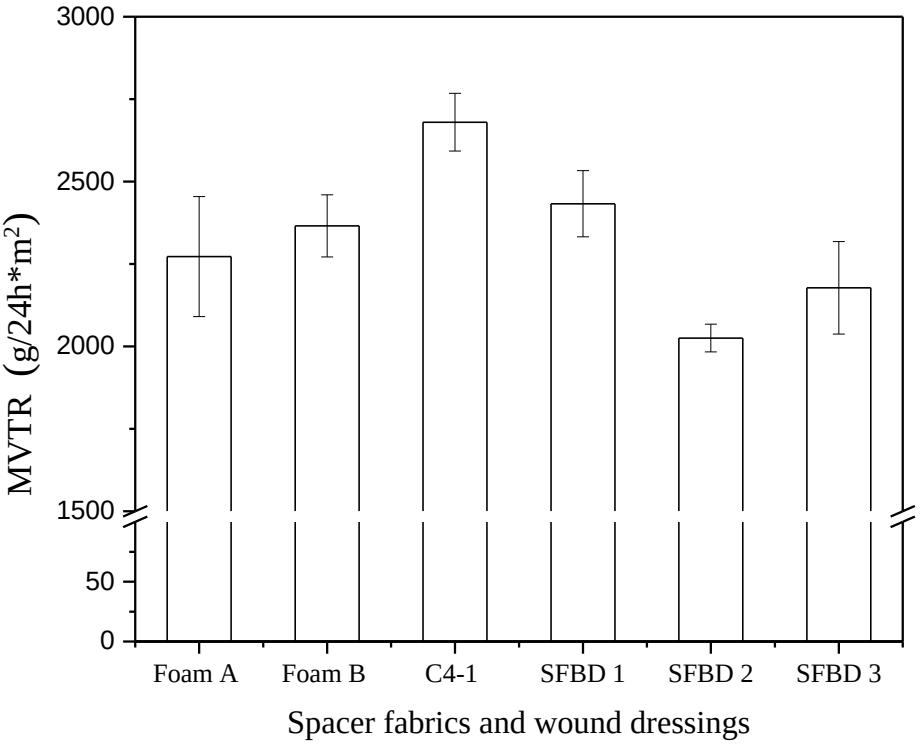


Figure 6.8 The MVTR of spacer fabrics and dressings in contact with water.

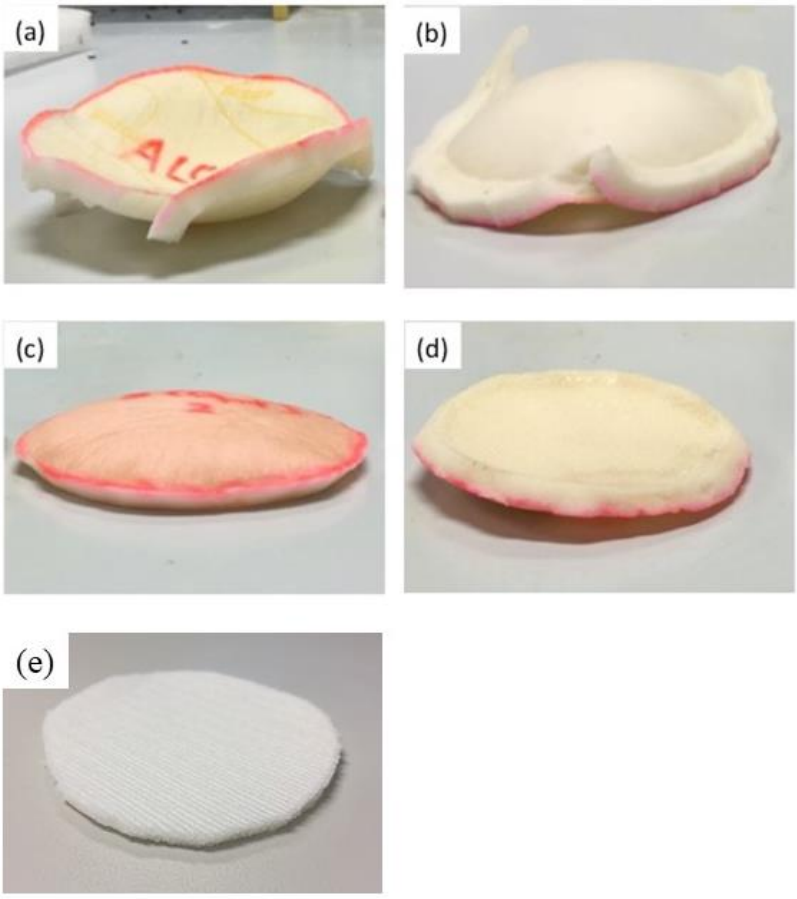


Figure 6.9 The pictures of (a) the outer surface of Foam A, (b) the wound contact layer of Foam A, (c) the outer surface of Foam B, (d) the wound contact layer of Foam B and (e) spacer fabric after absorbing water.

6.4 Conclusion

In this chapter, spacer-fabric-based dressings were compared with three types of commercial dressings to evaluate their performance while using as absorbent dressings for exuding wounds. Untreated spacer fabric C4-1 and spacer-fabric-based dressings treated with the electrospun nanofibrous membrane (SFBD 1), fluorocarbons (SFBD

2) and TiO_2 nanosol (SFBD 3) were used. Commercial dressings including two foam dressings and one alginate dressing were compared.

Different performance indicators including the wettability, absorbency, moisture transmission, air permeability, extensibility and water contact angle tests were tested. According to the experimental results and analyses, the following conclusions can be drawn.

a) The wound contact surface of spacer fabric would be immediately wetted while contacting with the wound bed. This is important for wound care that dressings should absorb exudates quickly to avoid fluid collecting around the wound and adjacent intact skin.

b) The absorbency of liquid containing Na^+ and Ca^{2+} ions of the spacer fabric was better than that of Foam B and Alginate. A large amount of liquid absorption extends the dressing period and reduces the frequency of dressing change. The liquid retention sustains a moist environment for wound healing.

c) The extensibility of foam dressings was poorer than that of spacer fabric in both weft and warp directions. The extensibilities of Alginate in two perpendicular directions were quite different and the breaking strength of Alginate was small. This indicates that spacer fabric was potential to be used as wound dressings in the light of their mechanical properties.

d) The water resistance of the spacer-fabric-based dressings was better than that of the commercial dressings. The spacer-fabric-based dressings could protect wounds better from contaminated fluids or even infection.

e) The air permeability of spacer-fabric-based dressings was much better than that of Foam A and Foam B. Alginate had a too high air permeability which made it a non-occlusive dressing requiring a secondary dressing.

f) The spacer fabric had an advantage in keeping a moist environment for wound and avoid maceration, which is one of the most important requirements for an absorbent dressing. The MVTRs of SFBD 2 and SFBD 3 were lower than that of Foam A and Foam B. The foam dressing deformed significantly after absorbing water, while the shape of spacer-fabric-based dressing did not change.

As a result, the spacer-fabric-based dressings could absorb large amount of fluid in a short period, and they were permeable for air and moist vapor while they were tended to keep a moist environment with low evaporation after absorbing. Spacer-fabric-based dressing can be a promising product for wound healing care.

Chapter 7 Biocompatibility and wound healing property of spacer-fabric-based wound dressing

7.1 Introduction

This chapter aims to assess the biocompatibility to evaluate the possibility to cause irritation reaction or toxic response and to study the wound healing speed of the treated spacer fabric as a dressing for wound occlusion.

As analyzed in chapter 6, the dressing properties of the treated spacer fabric revealed that the treated spacer fabric was promising to be used as an occlusive wound dressing. The spacer-fabric-based dressing had fast wetting speed and good absorbency to absorb exudates quickly from the wound. The moisture vapor permeability of spacer-fabric-based dressing was low to keep the wound in a moist environment. Meanwhile, the air permeability of spacer-fabric-based dressing was much higher than commercial foam dressings. Hence, from the aspect of physical properties, the spacer-fabric-based dressing was suitable for applying as exuding wound dressing.

Except the physical properties, the biocompatibility of wound dressing should also be considered. As wound dressing material would exposure to the body and bodily fluids,

biocompatibility testing is essential for this medical device to minimize any potential hazards to the patient. The U.S. Food and Drug Administration have adopted the ISO-10993 standard as its criteria for guiding the selection of biocompatibility testing for a given type of device. It is suggested that the tests should consist of *in vitro* and *in vivo* assessments that are relevant to the device application.

Biocompatibility including *in vitro* cytotoxicity and *in vivo* irritation and skin sensitization was evaluated in this study. The cytotoxicity of spacer-fabric-based dressing was measured *in vitro* using L929 mouse fibroblast cells. As wound dressing would directly contact with wound, the *in vivo* irritation and skin sensitization was tested by intracutaneous injection in rabbits. In addition, *in vivo* wound healing study was also implemented using a mouse model with full thickness-skin incisions.

7.2 Experimental

7.2.1 Materials

The designed spacer-fabric-based dressing with satisfied performance was applied to evaluate their biocompatibility and wound healing property. Spacer fabric C4-1 was processed with antimicrobial treatment and water resistant treatment.

As mentioned above, spacer fabric C4-1 was knitted with a 14-gauge STOLL CMS 822 computerized flat knitting machine. The outer single jersey layers were knitted with single polyester/spandex (100D/40D) yarn provided by Tailin (Zibo, China) Textile Co., Ltd. The spacer layer was knitted with 4 needle connecting distance using 32S/2 bleached cotton yarns provided by Meikesi (Dongguan, China) Yarn Co., Ltd.

For the antimicrobial treatment, the spacer fabric C4-1 was treated with a solution of 1 g/L $AgNO_3$ (analytical grade, from VWR Austria). The pH of the solution was adjusted to 6 by using 9.814 g/L (0.1M) CH_3COOK (99%, from Carl Roth GmbH, Austria) as a buffer. The fabric was immersed in 500 ml solution at 40 ^oC for 1h. Then, fabric was padded (type HVF-33593 padder from Werner Mathis AG) with 1 bar padding pressure and dried at 60 ^oC for 30 min. The layer on the top when padding and drying was marked as top layer, and the layer on the bottom when padding and drying was marked as bottom layer.

After the antimicrobial treatment, spacer fabric was treated with TiO_2 nanosol water resistant agent on its top layer. The reason to choose TiO_2 nanosol was that it had better biocompatibility and comparable water resistance. The prepared TiO_2 nanosol solution of concentration 1 wt % was sprayed on the top layer of spacer fabric to obtain water resistance. A spraying equipment (HD-130, RUIYI, Taiwan) was used at a pressure of 0.4MPa and the moving rate was about 5mm/s. After spraying, the spacer fabric was dried at 80°C for 3 min and then cured at 160 ^oC for 3 min.

The treated spacer fabric was applied as an absorbent wound dressing. Its biocompatibility and wound healing property were evaluated with *in vitro* cytotoxicity study, intracutaneous study and *in vivo* wound healing study.

7.2.2 *In vitro* cytotoxicity study

The purpose of this study was to evaluate the cytotoxicity of the spacer-fabric-based dressing *in vitro*. This study was conducted based on the requirements of International Organization for Standardization 10993-5:2009, Biological evaluation of medical devices - Part 5: Tests for *in vitro* cytotoxicity, which was evaluated with MTT (methylthiazolyldiphenyl-tetrazolium bromide) method.

7.2.2.1Extraction

The spacer-fabric-based dressing was extracted in the cell culture media Minimum Essential Medium (MEM). Blank control, negative control and positive control were carried out. In blank control, the culture media MEM was supplemented with 10% fetal bovine serum, 100 IU/ml penicillin and 100 μg/ml streptomycin. Marketed products were used in negative control and positive control. High density polyethylene

was used as negative control article as there was no active ingredient in it. Powder-free latex gloves made of natural rubber latex was used as positive control article.

Table 7.1 The extraction conditions of the *in vitro* cytotoxicity study

	Test article	Negative control	Positive control	Blank control
Extraction ratio	3 cm^2: 1ml	60 cm^2: 20 ml	120 cm^2: 20ml	/
Sample amount	60 cm^2	56 cm^2	120 cm^2	/
Extraction vehicle volume	20 ml	18.7 ml	20 ml	20 ml
Extraction condition	37°C, 24 hours	37°C, 24 hours	37°C, 24 hours	37°C, 24 hours
Condition of extracts	Clear No Particluate	Clear No Particluate	Clear No Particluate	Clear No Particluate

The extracts of samples were used in the cell culture process. Prior to extraction, the test article was placed in a pouch and subject to autoclave sterilization at 121 °C for 15 min. The extracts were continuously agitated during the extraction. The MEM extraction method was conducted in the presence of serum to optimize extraction of both polar and non-polar components. The details of extraction samples are shown in Table 7.1. All extracts were not centrifuged, filtered or otherwise altered prior to testing. It was tested immediately after extraction.

7.2.2.2Cell culture method

Mammalian cell culture monolayer consisting of L929 mouse fibroblast cells was used. *In vitro* mammalian cell culture studies have been used historically to evaluate cytotoxicity of biomaterials and medical devices. L929 mouse fibroblast cells were propagated and maintained in flasks containing MEM at 37°C with 5% carbon dioxide (CO_2). For this study, 10 cm wells were seeded, labeled with passage number and date, and incubated at 37°C in 5% CO_2 to obtain subconfluent monolayers of cells prior to use. Aseptic procedures were used in the handling of the cell cultures.

After thawing from stock, the cells were passaged two to three times before using in the test. Cell cultures were removed from culture bottles by enzymatic digestion (trypsin/EDTA) and the cell suspension was centrifuged at 200 G for 3 min. The cells were then resuspended in culture medium and the cell suspension was adjusted at a density of 1×10^5 cells/ml. Using a multichannel pipette, dispense 100 µl culture medium only (blank) into the peripheral wells of a 96-well tissue culture microtiter plate. In the remaining wells, 100 µl of a cell suspension of 1×10^5 cells/ml were dispensed. The cells were incubated for 24 hours (5% CO_2, 37 ^oC, > 90% humidity) so that cells form a half confluent monolayer. The plate was examined under microscope to ensure that cell growth was relatively even across the microtiter plate.

After 24 h incubation, the culture medium was aspirated from the cells. Per well, 100 µl of treatment medium containing either the appropriate concentration of sample extract or the negatives control, or the positive control, or blank control were added. The cells then were incubated for 24 h (5% CO_2, 37 ºC, > 90% humidity).

After 24 h treatment, the plate was examined under a phase contrast microscope to identify systematic cell seeding errors and growth characteristics of control and treated cells. After the examination of the plates, the culture medium was carefully removed from the plates. Subsequently, 50 µl of MTT solution was added to each test well and the plate was further incubated for 2 h in the incubator at 37 ºC. Then the MTT solution was discarded and 100 µl of isopropanol was added in each well. This plate was swayed and subsequently transferred to a microplate reader equipped with a 570 nm filter to read the absorbance (reference wavelength 650 nm).

7.2.2.3Evaluation and statistical analysis

A decrease in number of living cells results in a decrease in the metabolic activity in the sample. This decrease directly correlated to the amount of blue-violet formazan formed, as monitored by the optical density at 570 nm (OD_{570}, reference wavelength 650 nm). Equation 7.1 was used to calculate the reduction of viability compared to the blank.

$$\text{Viability \%} = R/R_0 \times 100 \qquad \text{Equation 7.1}$$

Where R is the average absorbency reading of testing groups, positive control group and negative control group; R_0 is the average absorbency reading of blank control group.

If the viability is reduced to < 70% of the blank, it has a cytotoxic potential. The 50% extract of the test sample should have at least the same or a higher viability than the 100% extract, otherwise the test should be repeated. The mean OD_{570} of blanks shall be $\geqslant$ 0.3. The mean of the blanks shall not differ by more than 15% from the mean of all blanks. The morphology of cells on the membranes was analyzed with microscope and photographed.

7.2.3 Animal intracutaneous reactivity study

As wound dressing would directly contact with wound, animal intracutaneous test was more reasonable than tests carried out on intact skin to determine the possible contact hazards of chemicals released from wound dressing. Spacer-fabric-based dressing was evaluated for the potential to cause irritation following intracutaneous injection in rabbits. This study was conducted based on ISO 10993-10, Biological evaluation of

medical devices-Part 10: Tests for irritation and skin sensitization. Animal experiments were carried out in Tianjin by Mid-Link Technology Testing Co., Ltd. The experiments complied with animal welfare regulations and the principles stated in the American Veterinary Medical Association's Guidelines were strictly followed throughout the experiment.

7.2.3.1Extraction

The test article was extracted in 0.9% sodium chloride solution (polar solution) and cotton seed oil (non-polar solution). Prior to extraction, the test article was placed in a pouch and subject to autoclave sterilization at 121 ºC for 15 minutes. The test article was cut into pieces with surface area of 150 cm^2. They were extracted according to the following conditions (Table 7.2).

The extracts were continuously agitated during the extraction. Sodium chloride solution and pure cotton seed oil which had no contact with the materials tested were used as negative control samples and were incubated under the same conditions. All extracts were not centrifuged, filtered or otherwise altered prior to dosing. It was dosed immediately after extraction.

Table 7.2 The extraction conditions of *in vivo* toxicity intracutaneous study

Group	Sodium chloride (polar)		Cotton seed oil (non-polar)	
	Test	Control	Test	Control
Extraction ratio	3 cm^2: 1ml	/	3 cm^2: 1ml	/
Sample amount	150 cm^2	/	150 cm^2	/
Extraction vehicle volume	50 ml	30 ml	50 ml	30 ml
Extraction condition	50 °C, 72 h	50 °C, 72 h	50 °C, 72 h	50 °C, 72 h
Condition of extracts	Clear No Particulate	Clear No Particulate	Clear No Particulate	Clear No Particulate

7.2.3.2Injection

Japanese white rabbit purchased from Tianjing Yuda Laboratory Animal Breeding Co., Ltd was used. Prior to treatment each animal was identified and weighed. All the rabbits were nulliparous and non-pregnant young adult females above 2.00 kg. Their acclimation periods were no less than 5 days. Within a 4 to 18 hours period before treatment, each rabbit was clipped free of fur from the back and both sides of the spinal column to yield a sufficient injection area. If necessary, swab the skin lightly with 35% isopropyl alcohol and allow it to dry prior to injection. Due to concern with the crowding and subsequent obscuring of injection sites, the test and control sites were cranial and caudal on the same side of the back as defined in the ISO standards.

A 0.2 ml dose of the appropriate test article extract was injected by the intracutaneous route into five separate sites on the right side of the back of each rabbit. Similarly, the corresponding control was injected on the left side of the back of each rabbit. No more than two test extracts and the corresponding controls were injected into each animal. Injections were about 2 cm apart. The appearance of the injection sites was noted immediately after injection. Observations for erythema and edema were noted for each injection site at 24, 48 and 72 hours after injection. Wipe the skin lightly with 35% isopropyl alcohol as necessary to facilitate scoring of the injection sites. The same tests were repeated on three animals numbered 9988, 9512, 9848. This study complied with animal welfare regulations and the principles stated in the American Veterinary Medical Association's Guidelines were strictly followed throughout the experiment.

7.2.3.3Evaluation

Reactions were scored on a 0 to 4 basis. Other adverse changes at the injection sites were also noted. The reactions were evaluated according to the subjective rating scale as shown in Table 7.3.

All erythema grades and edema grades (24, 48 and 72 hours) separately for each test and control for each individual animal were calculated. The mean score of spacer-fabric-based dressing or control on each individual animal was calculated by dividing

each of the totals by 15 (3 scoring time points × 5 sites). The overall mean for each test and control were calculated by adding the scores for the 3 animals and divide by 3. The difference between the overall mean score of the test article extracts and corresponding control extracts was calculated by subtracting the overall mean score for the control from the overall mean score for the test article extract. The requirements of the test are met if the difference is 1.0 or less.

Table 7.3 Grading criteria of the change of *in vivo* intracutaneous injected animal.

Score	Erythema and eschar formation	Edema formation
0	No erythema	No edema
1	Very slight erythema (barely perceptible)	Very slight edema (barely perceptible)
2	Well-defined erythema	Well-defined edema (edges of area well-defined by definite raising)
3	Moderate erythema	Moderate edema (raised approximately 1 mm)
4	Severe erythema (beet redness) to eschar formation preventing grading of erythema	Severe edema (raised more than 1 mm, and extending beyond exposure area)

7.2.4 *In vivo* wound healing study

The *in vivo* wound healing study aims to observe the wound healing process when a spacer-fabric-based dressing was applied on the full-thickness wound. Mice weighing 30 g were used in this study. After being anesthetized with diethyl ether and clipping dorsal hair, full-thickness square wounds with 15 mm × 15 mm area were prepared on the upper back of each mouse using a sharp pair of scissors and a scalpel. A piece

of spacer-fabric-based dressing was with the same area 15 mm × 15 mm was fixed onto the wound. The size of the dressing was chosen to keep it closely contact with wound. The same full thickness square wounds with 15 mm × 15 mm area were also prepared as a control wound. The control wound was treated with cotton gauzes. The changes in wound area were measured using a slide caliper, and at day7, day14, and day 21 after initial wounding. This animal experiments were carried out in Tianjin by Mid-Link Technology Testing Co., Ltd. The experiments complied with animal welfare regulations and the principles stated in the American Veterinary Medical Association's Guidelines were strictly followed throughout the experiment.

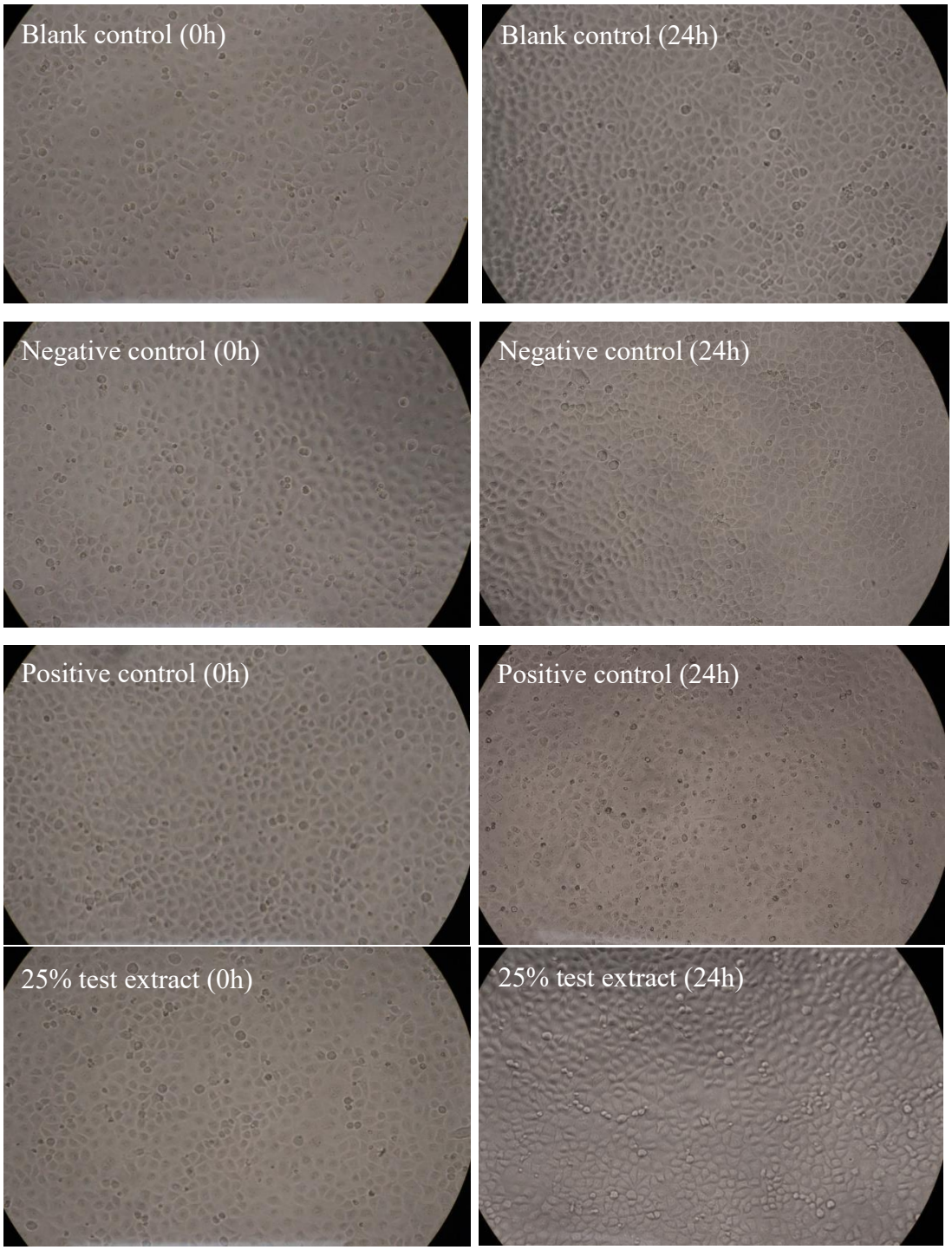
7.3 Results and discussion

7.3.1 *In vitro* cytotoxicity study

As wound dressing is a kind of medical devices that comes into contact with injured skin, it is necessary to determine the biological response of mammalian cells *in vitro* using appropriate biological parameters. The *in vitro* cytotoxicity of spacer-fabric-based dressing was assessed according to MTT method in standard ISO 10993 by microscopic observation and optical density evaluation.

To identify the potential morphological changes of L929 mouse fibroblasts induced by spacer-fabric-based dressing, the microscope images of fibroblast cells grown in

blank control, negative control, positive control and test extracts with concentration of 25%, 50%, 75%, 100% in 0h and 24h are presented in Figure 7.1.



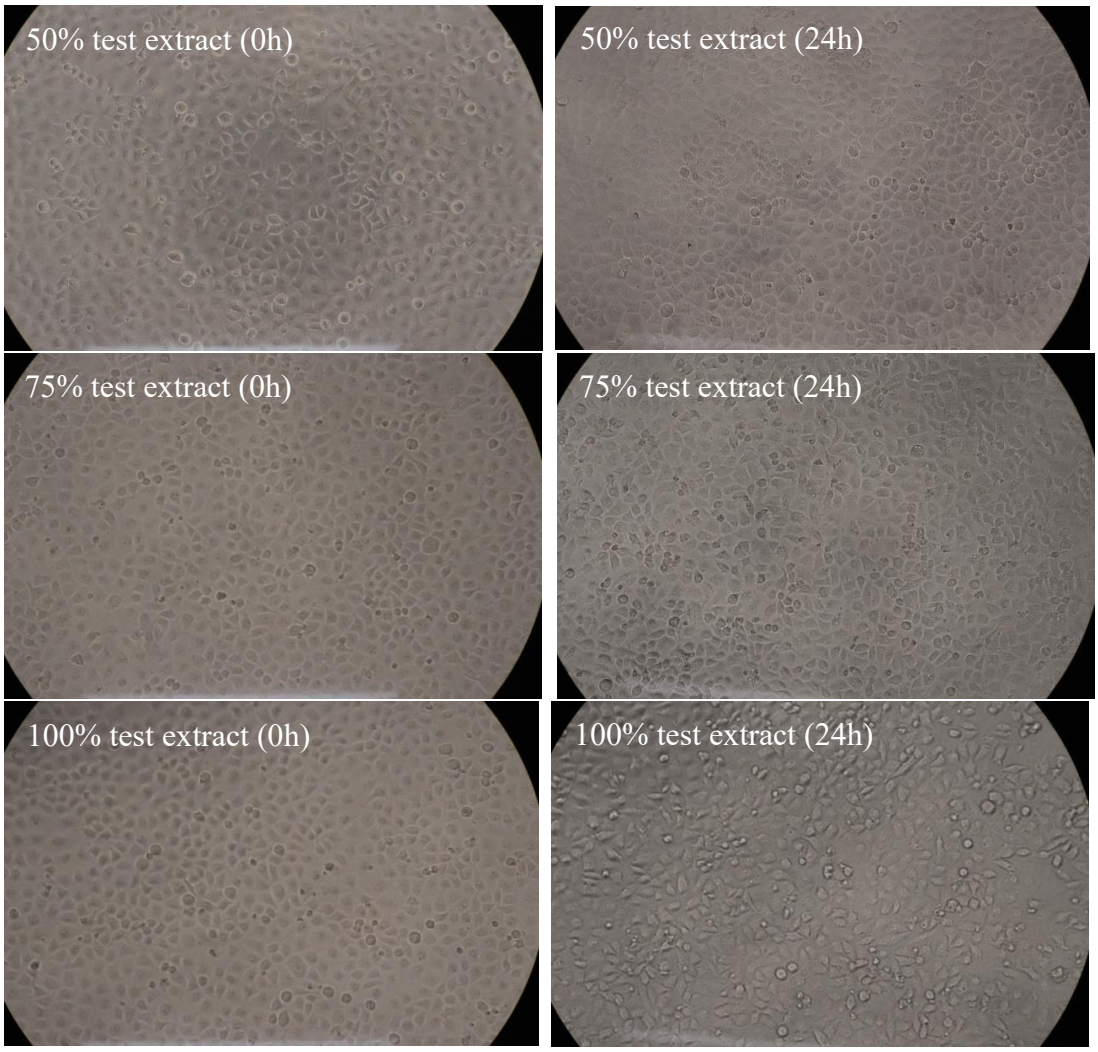


Figure 7.1 Microscope images of fibroblast cells grown in blank control, negative control, positive control and test extracts with concentration of 25%, 50%, 75%, 100% in 0h and 24h (40 ×).

Normally, L929 mouse fibroblast cells have spindle-like shapes, and they are large, adherent cells growing as a confluent monolayer fill in the entire surface area of the bottom of the culture dish, as shown in the blank control images. No or little damage could be found in negative control comparing with blank control cells. Substantial changes in cell morphology were detected microscopically in positive control after

exposure with the extract for 24h. Prominent cell lysis and cell debris were observed in positive control, where the cells lost their spindle shape and some detached from the bottom. For the 25%, 50%, 75% and 100% test extracts, the morphological change was not obvious. Fibroblast cells kept their spindle shape and no cell lysis was found in test extracts.

The decrease in number of living cells was monitored by OD values. To demonstrate the effectiveness of the tests, the OD values of the two blank controls are presented in Table 7.4. The mean OD_{570} of blanks were higher than 0.3, and the mean of the blanks did not differ by more than 15% from the mean of all blanks, which met all the acceptance criteria of quality control.

Table 7.4 OD values of blank controls of *in vitro* cytotoxicity study.

Group	OD value							
	1	2	3	4	5	6	Mean	
Blank control 1	0.469	0.448	0.458	0.5	0.478	0.435	0.465	0.482
Blank control 2	0.484	0.525	0.507	0.479	0.532	0.468	0.499	

The cell viability of MTT assay was calculated from OD values and is shown in Figure 7.2. MTT assay results were in agreement with light microscopic observations. Powder-free latex gloves made of natural rubber latex was used as positive control article. The positive control should provide a reproducible cytotoxic response. The cell viability result of positive control extract (2.91 %) shows its cytotoxicity. High density

polyethylene was used as negative control article as there was no active ingredient in it. The negative control extract with the cell viability of 98.74 % did not show cytotoxic potential. The blank controls, negative controls, and the positive controls performed as anticipated.

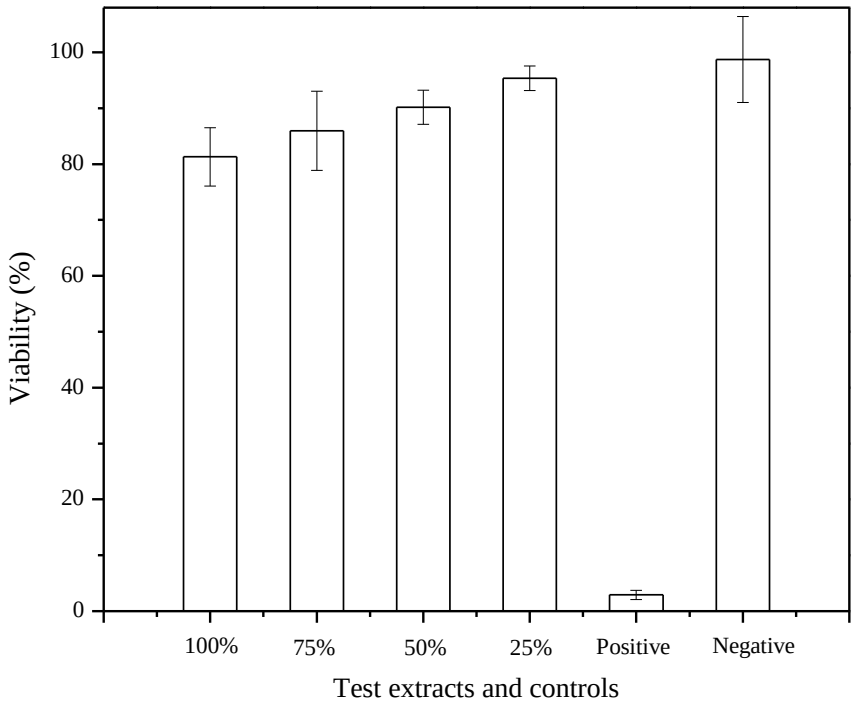


Figure 7.2 Cytotoxic effects of spacer-fabric-based dressing on L929 fibroblasts after 24 h incubation time using extraction concentrations of 25%, 50%, 75%, 100%. (The cell viability was determined by MTT assay and was shown as mean ±SD of six determinations.)

The extracts of spacer-fabric-based dressing with four different concentrations (25%, 50%, 75%, 100%) were cultured with L929 mouse fibroblasts for 24h. All test extracts caused a decrease in L929 cell proliferation from the concentration of 25% (cell viability 95.38%), and their effect was massive at the highest concentration (100%), with cell viability of 81.31%. The magnitude of the cytotoxic effects of all test extracts was found to be concentration dependent. The 50% extract of the test sample showed higher viability (90.20%) compared with that of 100% extract, which met the test requirements. According to the standard ISO 10993-5, reduction of cell viability by more than 30% is considered a cytotoxic effect. This indicated that the MEM test extracts of spacer-fabric-based dressing could be considered no cytotoxicity potential on L929 mouse fibroblast cells.

7.3.2 Animal intracutaneous reactivity study

As human tissue contact is involved in wound dressing application, it is necessary to assess intracutaneous reactivity of sample extract with regard to irritation and skin sensitization. The purpose of this testing was to determine the fitness of the spacer-fabric-based dressing for human use and to see whether the use of this medical device would have any potentially harmful physiological effects as erythema and/or edema.

The animal intracutaneous reactivity study examined two spacer-fabric-based dressing extracts, including extracts from polar sodium chloride solution and non-polar cotton seed oil, respectively. The extracts were intracutaneously injected in three Japanese white rabbits, and then the erythema and edema of rabbits were observed after 24h, 48h and 72h. Negative controls were used to compare with sample extracts. The photos of animals before treatment and 72 hours after injection are shown in Figure 7.3. The test article extract was intracutaneously injected into sites on the right side of the back of each rabbit, and the corresponding control was injected on the left side of the back of each rabbit. All injection sites appeared normal immediately following injection. All animals appeared normal throughout the study. The dressing appeared no irritation effect on directly human tissue.

The scores for erythema and edema observation 24h and 48h after injection are shown in Table 7.5. It was found that the animals did not show any grade of erythema and/ or edema after intradermal injection of the dressing extracts. The overall mean scores of extracts and controls and their difference are presented in Table 7.6. The mean score for irritation induced by the polar sodium chloride and non-polar cotton seed oil extracts of dressing was 0.0, respectively. The result showed that spacer-fabric-based dressing was non-irritant to the skin of rabbits. The irritation potential of either dressing extracts was the same with negative controls. Under the conditions of this study, the spacer-fabric-based dressing met the requirements of the test since the

difference between each test extract overall mean score and corresponding control overall mean score was 0.0 and 0.0 (less than 1.0) for the sodium chloride and cotton seed oil extracts test extracts, respectively. It can be concluded that the spacer-fabric-based dressing did not cause an intracutaneous reaction under the described test conditions.

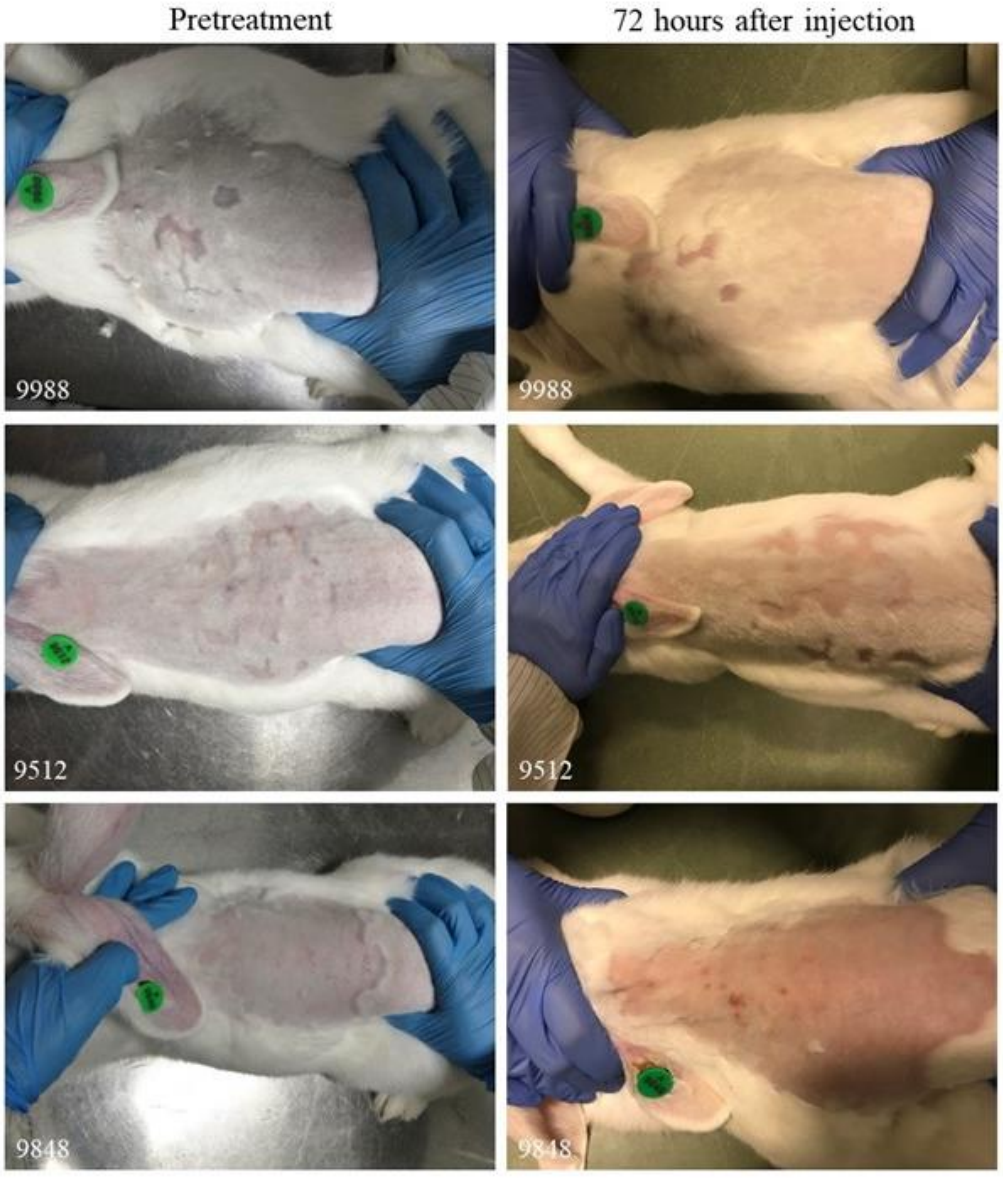


Figure 7.3 Photographs of animals before treatment and 72 hours after injection.

Table 7.5 Observation scores of individual animals 24h and 48h after injection.

Animal number	Sex	Body weight (kg)	Extraction vehicle	Scoring interval													
				24 hours				48 hours				72 hours					
				Test		Control		Test		Control		Test		Control			
				Erythema	Edema	Erythema	Edema	Erythema	Edema	Erythema	Edema	Erythema	Edema	Erythema	Edema		
9988	Female	2.56	Sodium chloride	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
			Cotton seed oil	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
9512	Female	2.55	Sodium chloride	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
			Cotton seed oil	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
9848	Female	2.60	Sodium chloride	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
			Cotton seed oil	0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		
				0	0	0	0	0	0	0	0	0	0	0	0		

Table 7.6 The overall mean scores of test groups and control groups and their difference.

Extract	Test group overall mean	Control group overall mean	Overall mean difference
Sodium chloride	0.0	0.0	0.0
Cotton seed oil	0.0	0.0	0.0

7.3.3 *In vivo* wound healing study

In the wound healing test, a single full-thickness square wound of skin (about 225 mm^2) was created on the back of each mouse. The changes of wound appearance on day 0, day 7, day 14 and day 21 are shown in photos in Figure 7.4. The unclosed wound area is presented in Figure 7.5, which determines the rate of wound closure as a function of time. The findings reflect that wound covered with spacer-fabric-based dressing healed rapidly and about 75% wound closure was achieved within 2 weeks. Within the first week, the unclosed wound areas of the two groups of wounds were similar. During the second week, wound covered with spacer-fabric-based dressing healed much faster than control wounds. After 21 days, the wound covered with spacer-fabric-based dressing was fully recovered, when the control wound still needed time to completely heal. In addition, the wound covered with spacer-fabric-based dressing contracted as a rectangle shape, whereas the control wound contracted as a circular shape. This indicated that control wound contracted evenly in different directions. In comparison, spacer-fabric-based dressing accelerated the wound closure

in the horizontal direction, which led to the rectangle shape of the unclosed wound. However, the adherence of spacer-fabric-based dressing was found to be adherent to the wound, which should be further improved to reduce the wound healing interruption. As a result, spacer-fabric-based dressing accelerated full thickness wound healing when comparing with cotton gauze.

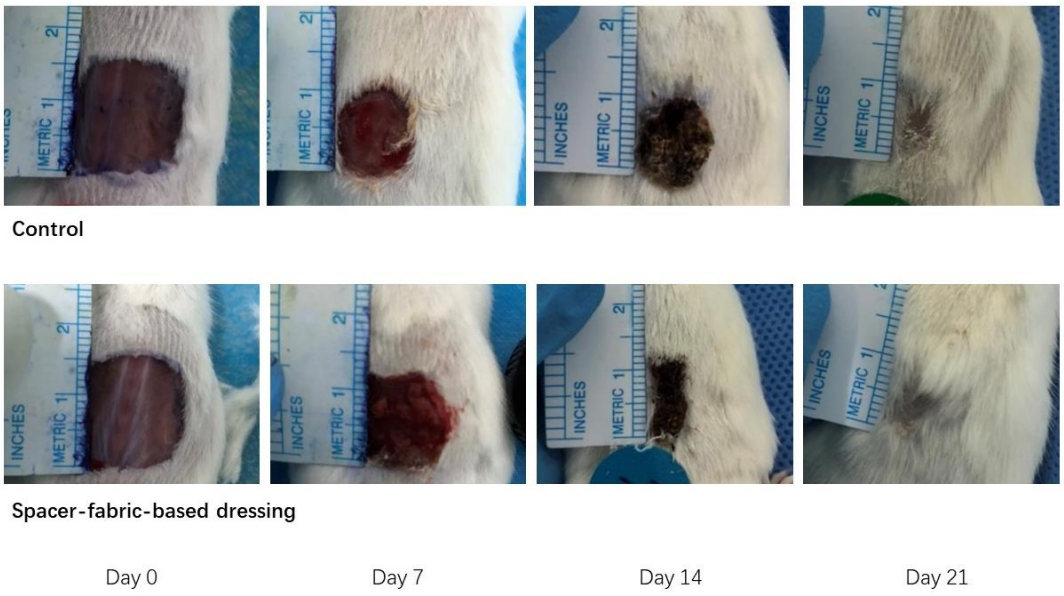


Figure 7.4 Photographic findings of wounds covered with spacer-fabric-based dressing and controls.

(Each wound on the indicated day is representative of three wounds.)

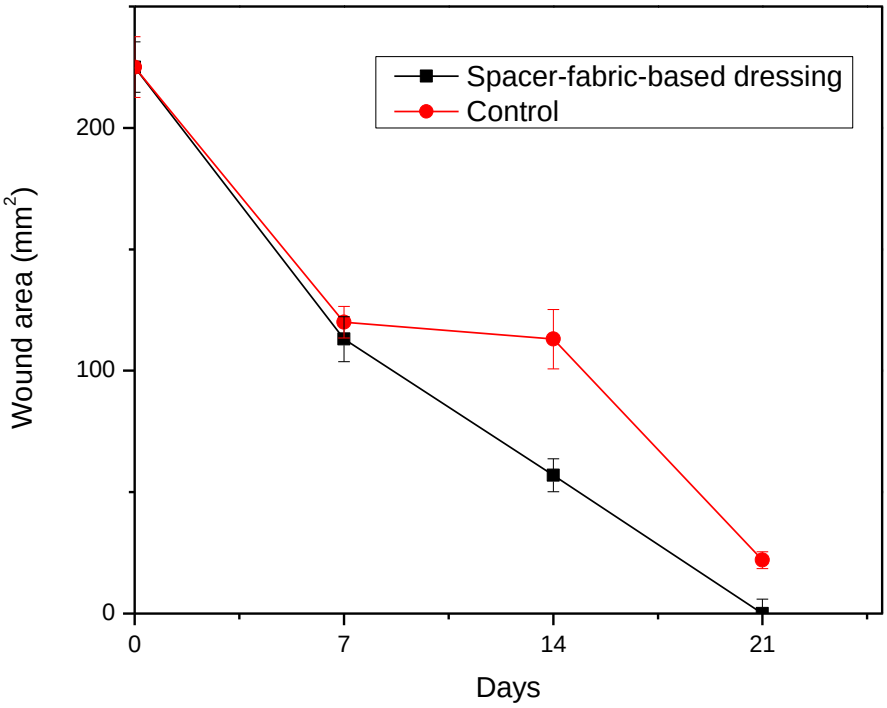


Figure 7.5 Closure of wounds covered with spacer-fabric-based dressing and controls.

7.4 Conclusion

For the *in vitro* cytotoxicity study, fibroblast cells kept their spindle shape and no cell lysis was found in test extracts. The blank controls, negative controls, and the positive controls performed as anticipated. The reduction of cell viability of test samples was less than 30%. Both the morphology of fibroblasts and cell viability indicate that the spacer-fabric-based dressing could be considered no cytotoxicity potential on L929 mouse fibroblast cells.

The animal intracutaneous reactivity study examined two spacer-fabric-based dressing extracts, including extracts from polar sodium chloride solution and non-polar cotton seed oil, respectively. It was found that the animals did not show any grade of erythema or edema after intradermal injection of the dressing extracts. The spacer-fabric-based dressing did not cause an intracutaneous reaction with regard to irritation and skin sensitization under the described test conditions.

The *in vivo* wound healing test showed that spacer-fabric-based dressing accelerated full thickness wound healing when comparing with cotton gauze. 75% wound closure was achieved in wound covered with spacer-fabric-based dressing within 2 weeks. After 21 days, the wound covered with spacer-fabric-based dressing was fully recovered, when the control wound still needed time to completely heal. Spacer-fabric-based dressing accelerated the wound closure in the horizontal direction, which led to the rectangle shape of the unclosed wound. In conclusion, the spacer-fabric-based dressing could accelerate wound healing with no cytotoxicity and intracutaneous irritation.

Chapter 8 Conclusions and future works

8.1 Conclusions

In order to improve the exuding wound care condition to facilitate wound healing process, weft-knitted spacer fabrics with good dressing properties have been proposed to be used as absorbing wound dressing materials. This study established a clear picture for designing and fabricating a functional spacer-fabric-based wound dressing for exuding wound, by improving the wettability, absorbency, permeability, thermal property, antimicrobial property and water resistance. The spacer-fabric-based dressings were compared with commercial wound dressings in dressing properties to evaluate their potential to be applied as wound dressing. In addition, the biocompatibility studies including *in vitro* cytotoxicity study and *in vivo* intracutaneous reactivity study were carried out to evaluate the possibility to cause irritation reaction or toxic response. The wound healing speed of the spacer-fabric-based dressing was studied by *in vivo* wound healing tests.

8.1.1 Design and fabrication of spacer-fabric-based dressing

Spacer-fabric-based dressing was firstly designed according to the requirements of exuding wound care. Three layers were included in the designed dressing. The wound

contact layer should be a hydrophobic with quick moisture transmission rate, and the outer layer should be waterproof to protect the wound.

Twelve spacer fabrics with different spacer yarn types, number of surface yarn and number of connecting distance were produced and the effects of fabric structures on dressing properties were assessed. According to the ANOVA analysis results, spacer fabrics with longer spacer yarn connecting distance had shorter wetting time, better absorbency and thermal insulation, but poorer WVTR. Spacer fabrics knitted with two surface yarns had better absorbency and better thermal property, but poorer air permeability than spacer fabrics knitted with only one surface yarn. Spacer fabrics knitted with Tencel spacer yarn had much shorter wetting time and better air permeability than spacer fabrics with cotton spacer yarn. However, spacer fabrics with cotton spacer yarns can retain more water inside spacer zone than spacer fabrics with Tencel spacer yarns. Considering their good air permeability and appropriate absorbency and WVTR, spacer fabric knitted with cotton spacer yarn with 4 needle connecting distance (C4-1) was selected as the basic material of designed dressing.

8.1.2 Antimicrobial treatment

The spacer fabric C4-1 was treated with silver antibacterial agent. The silver distributions were compared between the spacer fabric and 4-layered cotton fabric.

The results indicate that the silver contents of middle layers of the 4-layerd cotton fabric were lower than their surface layers, whereas the middle layer of the spacer fabric had much higher silver content than its two surface layers. For the antimicrobial properties of silver-containing spacer fabrics, 100% reductions in viability were observed for both the gram-positive *Staphylococcus aureus* and the gram-negative *Klebsiella pneumoniae* after only 1 h. The way to absorb wound exudates and kill bacteria within the dressings reduces silver concentration on the wound bed, and therefore this could be an efficient way to lower the potential of silver entering human body, and prevent the silver toxicity and wound-healing delay.

8.1.3 Water resistant treatment

Three water resistant treatments were applied on spacer-fabric-based dressing to keep contaminated fluid and harmful substance away from the wound. Spacer fabric was treated with electrospun nanofibrous membrane, fluorocarbons agent NUVA N2114 and TiO_2 nanosol, and they were named as SFBD 1, SFBD 2, SFBD 3. The treated spacer fabrics were evaluated by the water contact angle test and air permeability test. Spacer fabrics treated with fluorocarbons and TiO_2 nanosol had higher water resistance than spacer fabric treated with electrospun nanofibrous membrane. However, the air permeability of the later one was better than that of the former ones.

8.1.4 Comparison with commercial absorbent wound dressings

Spacer-fabric-based dressings were compared with three types of commercial dressings to evaluate their performance while using as absorbent dressings for exuding wounds. Untreated spacer fabric C4-1 and SFBD 1, SFBD 2, SFBD 3 were compared with commercial dressings including two foam dressings and one alginate dressing.

The wound contact surface of spacer fabric would be immediately wetted while contacting with the wound bed. The absorbency of liquid containing Na^+ and Ca^{2+} ions of the spacer fabric was better than that of Foam B and Alginate. The extensibility of foam dressings was poorer than that of spacer fabric in both weft and warp directions. The breaking strength of Alginate was small. This indicates that spacer fabric was potential to be used as wound dressings in the light of their mechanical properties. The water resistance of the spacer-fabric-based dressings was better than that of the commercial dressings. Also, the air permeability of spacer-fabric-based dressings was much better than that of Foam A and Foam B. Alginate had a too high air permeability which made it a non-occlusive dressing requiring a secondary dressing. The spacer fabric had an advantage in keeping a moist environment for wound and avoiding maceration, which is one of the most important requirements for an absorbent dressing. In addition, the foam dressing deformed significantly after absorbing water, while the shape of spacer-fabric-based dressing did not change.

As a result, the spacer-fabric-based dressings could absorb large amount of fluid in a short period, and they were permeable for air and moist vapor while they were tended to keep a moist environment with low evaporation after absorbing. Spacer-fabric-based dressing can be a promising product for wound healing care.

8.1.5 Biocompatibility and wound healing property of spacer-fabric-based wound dressing

For the *in vitro* cytotoxicity study, fibroblast cells kept their spindle shape and no cell lysis was found in test extracts. The blank controls, negative controls, and the positive controls performed as anticipated. The reduction of cell viability of test samples was less than 30%. Both the morphology of fibroblasts and cell viability indicate that the spacer-fabric-based dressing could be considered no cytotoxicity potential on L929 mouse fibroblast cells.

The animal intracutaneous reactivity study examined two spacer-fabric-based dressing extracts, including extracts from polar sodium chloride solution and non-polar cotton seed oil, respectively. It was found that the animals did not show any grade of erythema or edema after intradermal injection of the dressing extracts. The spacer-fabric-based dressing did not cause an intracutaneous reaction with regard to irritation and skin sensitization under the described test conditions.

The *in vivo* wound healing test showed that spacer-fabric-based dressing accelerated full thickness wound healing when comparing with cotton gauze. 75% wound closure was achieved in wound covered with spacer-fabric-based dressing within 2 weeks. After 21 days, the wound covered with spacer-fabric-based dressing was fully recovered, when the control wound still needed time to completely heal. Spacer-fabric-based dressing accelerated the wound closure in the horizontal direction, which led to the rectangle shape of the unclosed wound. In conclusion, the spacer-fabric-based dressing could accelerate wound healing with no cytotoxicity and intracutaneous irritation.

8.2 Limitations

However, this work has some limitations. The first limitation is that the mechanical properties were changed after the antibacterial treatment and water resistant treatment due to the high temperature used in those treatments. The high temperature affected the elastic recovery of spandex which led to the reduction of elasticity and extensibility of spacer fabrics. The second limitation is that the *in vivo* wound healing test only carried out with spacer-fabric-based dressings. Since the limitation of experimental conditions, the *in vivo* wound healing test did not implement with commercial dressings. The third limitation is that the spacer-fabric-based dressing was found to be

adherent to the wound, which affected the wound healing. It is beneficial to the wound if the adherence between spacer fabric and wound bed can be lowered.

8.3 Recommendations for future works

Based on the conclusions and limitations from this work, the application of spacer fabric as absorbent dressing for exuding wound can be further improved. First, it is recommended that the treatment temperature could be further lowered to keep the elasticity and extensibility of spandex, which also improves the mechanical properties of spacer- fabric-based dressing. The second recommendation is that the *in vivo* wound healing test can be carried out with commercial dressings in the same condition with test on spacer fabric to prove the efficiency of spacer-fabric-based dressing. In addition, after strictly examined the safety of the spacer-fabric-based dressing, clinic trails are expected to be carried out. The third recommendation is to lower the adherence of spacer fabric to the wound. Application of coating or improving the textile structure can be effective methods to lower the adherence and therefore to reduce wound healing interruption.

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