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Spacer fabric based exuding wound dressing - Part I: Structural design, fabrication and property evaluation of spacer fabrics

Abstract: Exuding wound dressing is used to help the wound healing. Currently commercial dressings for heavily exuding wounds still have some drawbacks, such as poor integrity, poor air permeability, low water vapor transmission, and need of a secondary dressing on the top. To overcome these drawbacks, a new type of wound dressing based on three-layer spacer fabric structure is proposed in this study. The study includes two parts. As the first part, it focuses on the design, fabrication and property evaluation of spacer fabrics which can be used for wound dressing. Twelve different types of spacer fabrics were first fabricated. Then, different properties including wettability, absorbency, permeability and thermal insulation, were tested and evaluated. The statistical analysis was also conducted to evaluate the effects of structural and yarn parameters on the properties of the spacer fabrics. Based on the testing results, two suitable spacer fabrics were finally selected as the basis wound dressing material. It is expected that this study could promote the application of spacer fabrics in medical area.

Keywords
spacer fabric, wound dressing, absorbent dressing, exuding wound.

Introduction

The market potential for wound care is continuously increasing in recent years. Especially, the growth and aging of population are driving the demand for wound dressings with multi-functions [1, 2]. Nowadays, numerous types of wound dressing made of different materials to have different properties and performances are available for the management of different kinds of wounds [3].

The performance requirements of a wound dressing depend on the wound healing process. According to references [4-8], the wound healing process can be generally split into four phases: a) the coagulation and hemostasis phase immediately starting after injury; b) the inflammatory phase occurring shortly after injury to tissue, during which swelling takes place; c) the proliferation period, in which new tissues and blood vessels are formed; and d) the maturation phase, in which tissues laid down during the proliferation stage are remodeled. Medium to heavily exuding often appears in the middle period and the aim of applying wound dressing in this period is to absorb exudate and accelerate wound healing [9].

Since George Winter [10] 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 [11]. Based on this principle, sophisticated dressings which could provide moist, absorbent, interactive and non-toxic environments for wound healing have been developed [12].

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 [13]. 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 [4, 14-16]. It should be noted that the medium to heavy exuding period is a critical period which is difficult to be managed [17]. However, currently 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.

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 [18, 19]. The 3D nature of spacer fabric structure makes them an ideal candidate for this kind of application [20]. 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 [21]. Spacer fabrics also guarantee a good distribution of pressure and good press elastic behavior [22], 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 [23]. 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 [24-26]. 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.

Numerous research works have recently demonstrated promising applications of spacer fabrics as protective devices, compression bandages and incontinence pads [4, 27-30]. It has been shown that spacer fabrics have good moisture management and wicking property. R. Bagherzadeh[31] 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 [32] 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 generate thermal comfort and regulate human body temperature when fabricated with different types of yarns on different layers [33]. Spacer fabrics can have high water absorbency and be used as absorbent dressings. Angela Davies [34] 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 large amount of liquid [35]. Tilak Dias [36] et al. found that knitted structures with high porosity absorb more water than those with low porosity. Shuk-fan Tong [37] 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.

This study aimed to design and fabricate a new type of spacer fabric based wound dressing having high liquid absorption and retaining, at the same time having high breathability and extensibility. The study includes two parts. In part I, various spacer fabrics with hydrophobic surface layers and absorbent inner layer were first designed and fabricated using weft knitting technology. Then, their properties including wettability, absorbency, permeability and thermal insulation were tested and evaluated in order to select suitable spacer fabrics for wound dressing use. In part II, the selected spacer fabrics were further covered with a layer of nanofibrous membrane on their outer layer surface via an electrospinning process in order to improve their waterproof property. Then, the nanofibrous membrane covered spacer fabrics were used as final wound dressings and compared with commercial products available from the market. It is expected that this study could further promote the application of spacer fabrics in medical area.

Materials and methods

Structural design of spacer fabric based dressing

The purpose of this study is to develop a new type of spacer fabric based exuding wound dressings with required performance. 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 good mechanical and thermal performance for comfortable wearing.

To achieve these requirements, a multi-functional dressing was designed based on three-layered spacer fabric structure. As shown in Figure 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. To enhance the waterproof property of the outer layer of dressing, at the same time to not affect its permeability, a permeable nanofibrous membrane was further added to cover the outer layer of spacer fabric after the spacer fabric had been knitted. The permeable nanofibrous membrane was a nonwoven structure which was formed via an electrospinning process by spraying nanofibers on the spacer fabric outer surface. The spacer 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 through 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 thermal property is mainly affected by the thickness of absorbent layer. In addition, 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. Based on this designed structure, a spacer fabric based dressing with good absorbency, permeability, extensibility and thermal property could be realized by the proper usage of yarns and knitting parameters.

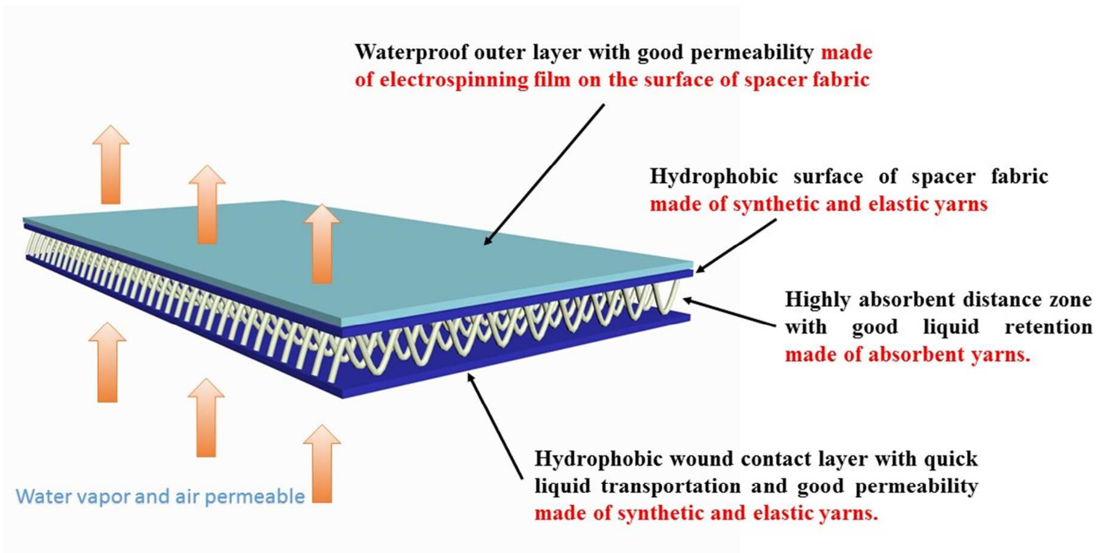
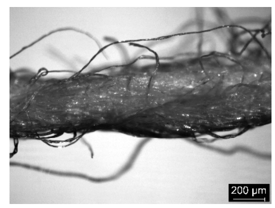
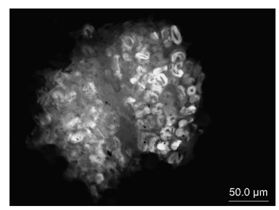
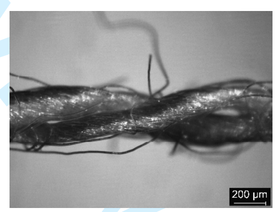
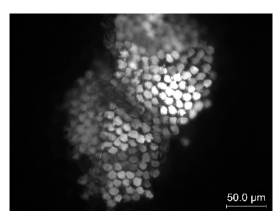


Figure 1. Wound dressing designed based on spacer fabric structure.

Fabrication of spacer fabrics

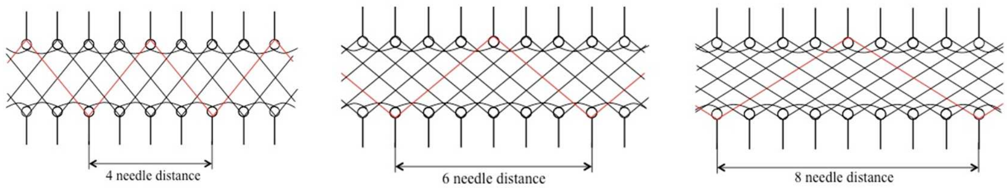
Spacer fabric structure is the backbone and base material of the designed dressing. Two fabrication processes, knitting and steaming, were carried out to obtain the designed fabrics. Spacer fabrics were first knitted with a 14-gauge STOLL CMS 822 computerized flat knitting machine due to simpler fabrication process and easy knitting parameter control as well as 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 is 1.0%. The spacer layer (distance zone) was knitted with different spacer yarn lengths (different spacer yarn connecting distances as shown in Figure 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. As this study is the preliminary investigation of the possibility of applying spacer fabrics as wound dressings, the bacterial problem was not discussed in this paper. 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 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 consitioned 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 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 °C for 30s using a HSL-611 steam iron produced by NAOMOTO Corporation, Japan. After the steaming treatment, the fabric samples were conditioned at 20 °C 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 typical fabricated spacer fabric is shown in Figure 3. The fabrication of the fourth layer of spacer fabric based wound dressing will be discussed in Part II of this study.



(a) (b) (c)

Figure 2. Spacer fabric structures with (a) 4, (b) 6, (c) 8 needle connecting distance.

Figure 3. 3D view of a typical fabricated spacer fabric.

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 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 4. These fabrics having different areal mass, thickness, surface stitch density, mass of spacer yarns and porosity, are also shown in Table 2. The porosity of spacer fabric was evaluated by using the pycnometric method [38, 39]. 5cm × 5cm samples were prepared and weighted respectively. The bulk density was calculated by dividing the weight measured with the sample volume. The porosity of samples was determined according to Formula (1).

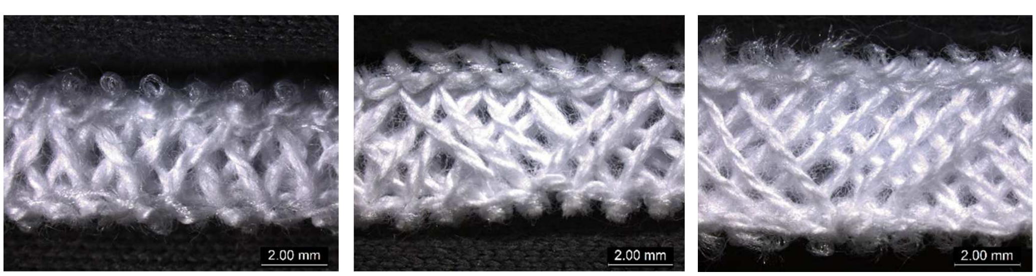
$$\text{Porosity (\%)} = 1-\rho_b/\rho_f \quad (1)$$

Where ρ_b is the bulk density of spacer fabrics and ρ_f is the fiber density.

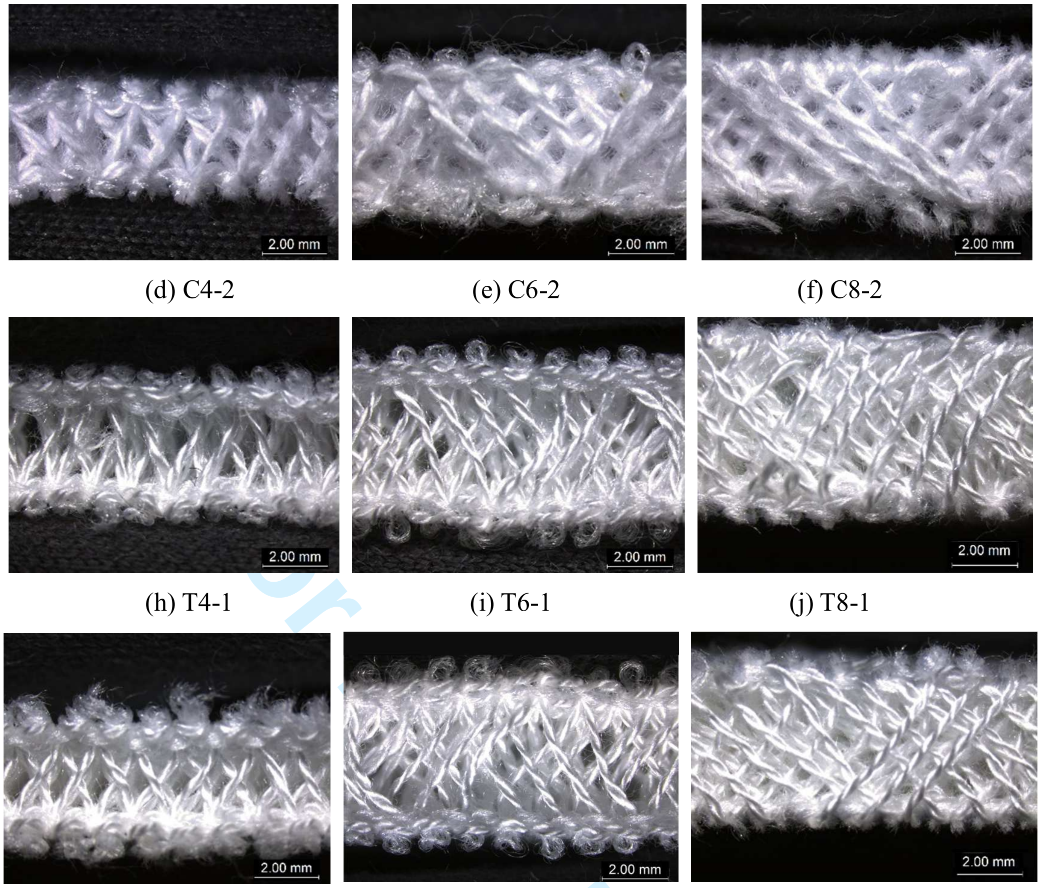
Table 2. Details of produced spacer fabrics.

Fabric code	Spacer yarn connecting distance (no. of needles)	Number of surface yarns	Type of spacer yarns	Fabric thickness (mm)	Areal mass of fabric (g/m^2)	Areal mass of spacer yarns (g/m^2)	Porosity (%)	Surface stitch density		
								Course direction (wales/cm)	Wale direction (courses/cm)	Stitch density (loops/cm^2)
C4-1	4	1	Cotton	3.253 (± 0.093)	540.4 (± 21.36)	435.6 (± 11.43)	41.73 (± 3.21)	8.6 (± 0.548)	13.0 (± 0.707)	112.0 (± 11.90)
C6-1	6	1	Cotton	3.736 (± 0.064)	684.7 (± 20.14)	578.2 (± 14.76)	32.49 (± 4.58)	8.6 (± 0.548)	13.2 (± 0.447)	113.6 (± 9.503)
C8-1	8	1	Cotton	4.860 (± 0.220)	885.6 (± 17.84)	770.2 (± 21.79)	27.44 (± 2.97)	8.2 (± 0.447)	14.2 (± 0.447)	116.6 (± 10.29)
C4-2	4	2	Cotton	3.388 (± 0.178)	712.2 (± 16.27)	488.2 (± 10.84)	20.91 (± 1.22)	8.1 (± 0.224)	16.4 (± 0.548)	132.8 (± 4.382)
C6-2	6	2	Cotton	3.820 (± 0.035)	837.2 (± 12.13)	615.8 (± 19.24)	16.12 (± 1.04)	8.0 (± 0.001)	16.4 (± 0.548)	131.2 (± 4.382)
C8-2	8	2	Cotton	4.548 (± 0.112)	923.3 (± 29.44)	743.8 (± 23.71)	15.60 (± 2.37)	7.5 (± 0.354)	15.8 (± 0.447)	118.5 (± 6.576)
T4-1	4	1	Tencel	3.343 (± 0.070)	616.4 (± 16.55)	484.8 (± 13.28)	25.43 (± 2.34)	9.7 (± 0.274)	15.0 (± 0.001)	145.5 (± 4.108)
T6-1	6	1	Tencel	4.052 (± 0.074)	773.4 (± 21.06)	648.2 (± 19.11)	15.55 (± 1.78)	8.9 (± 0.418)	16.2 (± 0.274)	144.1 (± 4.798)
T8-1	8	1	Tencel	4.547 (± 0.152)	899.0 (± 21.33)	779.7 (± 27.40)	9.09 (± 1.00)	8.9 (± 0.224)	15.8 (± 0.447)	140.6 (± 4.669)
T4-2	4	2	Tencel	3.387 (± 0.023)	738.3 (± 10.89)	499.8 (± 11.93)	8.09 (± 1.48)	8.8 (± 0.447)	15.9 (±0.224)	140.0 (± 8.063)
T6-2	6	2	Tencel	4.168 (± 0.114)	873.1 (± 24.88)	652.0 (± 19.34)	5.14 (± 0.55)	8.3 (± 0.274)	15.9 (± 0.224)	132.0 (± 5.657)
T8-2	8	2	Tencel	4.553 (± 0.157)	941.0 (± 32.10)	718.1 (± 18.52)	4.36 (± 0.91)	7.9 (± 0.224)	16.0 (± 0.001)	126.4 (± 3.578)

Note: Standard deviations are given in parentheses.



(a) C4-1 (b) C6-1 (c) C8-1



(d) C4-2 (e) C6-2 (f) C8-2

(h) T4-1 (i) T6-1 (j) T8-1

(k) T4-2 (l) T6-2 (m) T8-2

Figure 4. Cross-section of spacer fabrics.

From Table 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 higher thickness and areal mass, as well as higher areal mass of spacer yarns and smaller porosity. 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.

Property evaluation of spacer fabrics

The performance of the spacer fabrics fabricated was evaluated with different tests which are relevant to the dressing use. These tests include the wettability test, absorbency test, air permeability test and water vapor transmission test which are related to moisture management ability, and thermal property test which is related to thermal insulation performance. Wettability shows how fast the liquid entries spacer fabrics. Absorbency not only indicates how much liquid spacer fabrics can absorb, but also represents how much liquid can be retained inside spacer zones after draining. The tests for water vapor transmission present how fast the water evaporates from spacer fabrics, while air permeability test is to determine how difficult the air passes through spacer fabrics. All these tests were carried out in the standard atmosphere, which was 20 ^{o}C and 65% RH relative humidity. The testing method for each test is briefly described below.

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.

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 is the key to provide 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 into water for 2 min. Then, the sample was removed and drained for 30s. The weight of water absorbed by per $100cm^2$ of sample was calculated. Five specimens were tested for each type of fabric. The absorbency was calculated according to Formula (2).

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

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

Air permeability test. The air permeability test was carried out according to ASTM D737 on a 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.

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 with quick-drying adhesive cement. The distance between the surface of the water and the underside of the specimen was 10 ± 1mm at the beginning of 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 test was measured, respectively. The amount of water evaporated per m^2 per 24 h was calculated according to Formula (3). Three repeating tests were conducted for each type of fabric.

$$\text{WVTR } (g/(24h*m^2)) = (M_0-M_1)/A \qquad (3)$$
$$A = \pi d^2/4 \ (d=0.083m)$$

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

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 Formula (4).

$$Q\ (\%) = (1 - Q_2/Q_1) \times 100 \quad (4)$$

Where Q_1 is the q-max value without sample placed on testing area, J/ ^{o}C; Q_2 is the q-max value with sample placed on testing area, J/ ^{o}C.

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, $p \leqslant 0.0500$ indicated that the effects were significant.

Results and Discussion

Wettability and absorbency

The results of the wetting time of all the spacer fabrics are shown in Figure 5. A short wetting time implicates good wettability. From Figure 5 and the ANOVA results, it can be seen that the wetting time of spacer fabrics were 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 statistical significant (p = 0.2244).

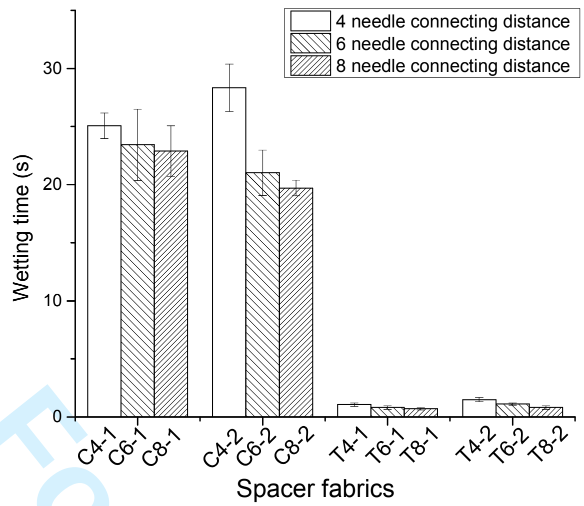


Figure 5. Wetting time of spacer fabrics.

The results of the absorbency of all twelve spacer fabrics are shown in Figure 6. 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 6 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 2), which make fabrics absorbing more water. The more the absorbent spacer yarns are contained in the spacer zone, the better the absorbency is.

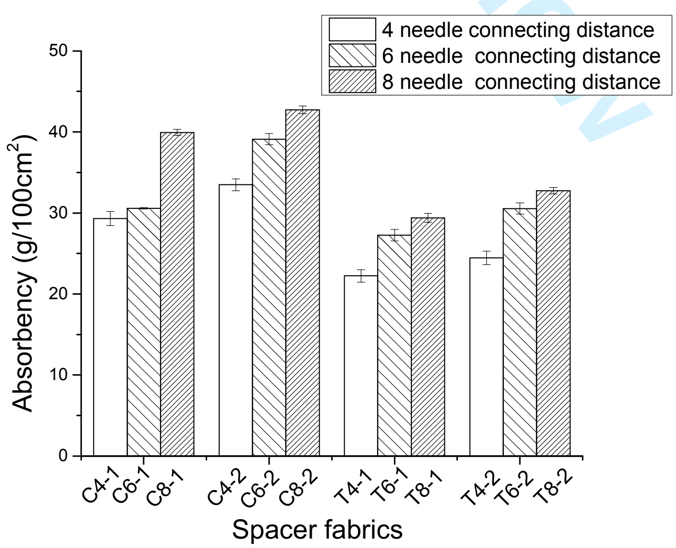


Figure 6. Absorbency of spacer fabrics.

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 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 and absorbency represents the amount of liquid absorbed by spacer fabrics, the wettability and absorbency were mainly affected by the areal mass of spacer yarns and the type of spacer yarns, and they can hardly be affected by the porosity.

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 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, keeping of a moist environment also depends on the evaporation of the liquid.

Permeability of water vapor and air

The testing results of WVTR are presented in Figure 7. 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 WVTR of spacer fabrics with two elastic yarns on surface is slightly lower than that of fabrics with one surface yarn, and the difference was significant (p = 0.0339). As shown in Table 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 no effect on the WVTR (p = 0.1092). Although the different fiber fineness and cross section of cotton and Tencel yarns (Table 1) may have effects on the WVTR, the effects were not significant when applying in a spacer fabric structure.

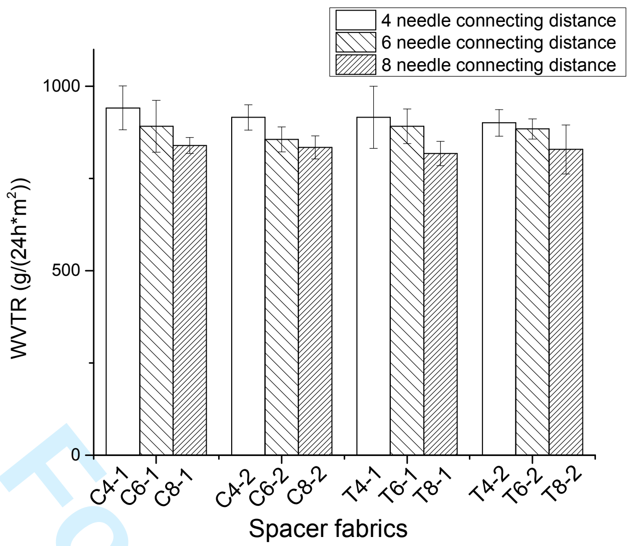


Figure 7. WVTR of spacer fabrics.

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 WVTR of wound dressings were suggested to be higher than that of normal skin (200-500 g/(24h*m^2)) to avoid infection [40]. The results show that the WVTR of all the spacer fabrics were between 800 and 1000 g/(24h*m^2), much higher than that of normal skin. Moreover, the WVTR of spacer fabrics is definitely lower than that of traditional cotton gauze or normal fabrics because of their higher thickness. In this regard, the WVTR of spacer fabrics was at a proper medium level and suitable for applying as wound dressings.

The results of air permeability are presented in Figure 8. The air permeability of spacer fabrics are 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).

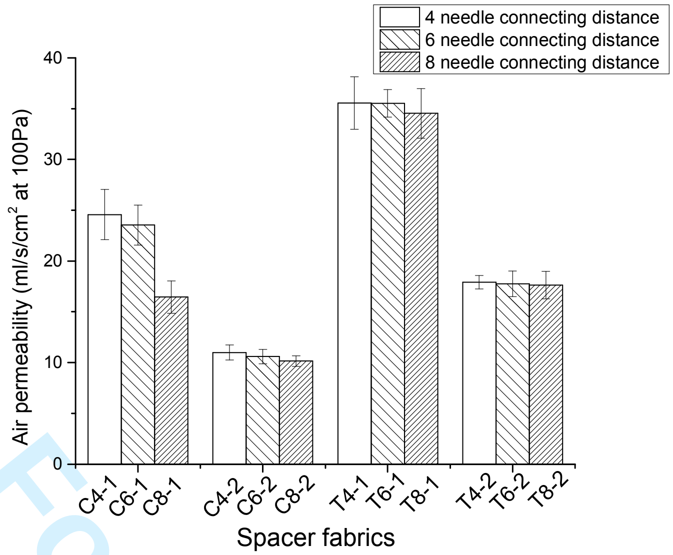


Figure 8. Air permeability of spacer fabrics.

From Figure 8, it can be also seen that the type of spacer yarns also significantly affected air permeability (p = 0.0097). As shown in Figure 8, 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 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 [4]. 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 have very good air permeability. Noticeably, the sample T4-1 possesses high permeability for both water vapor and air.

Thermal property

Figure 9 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).

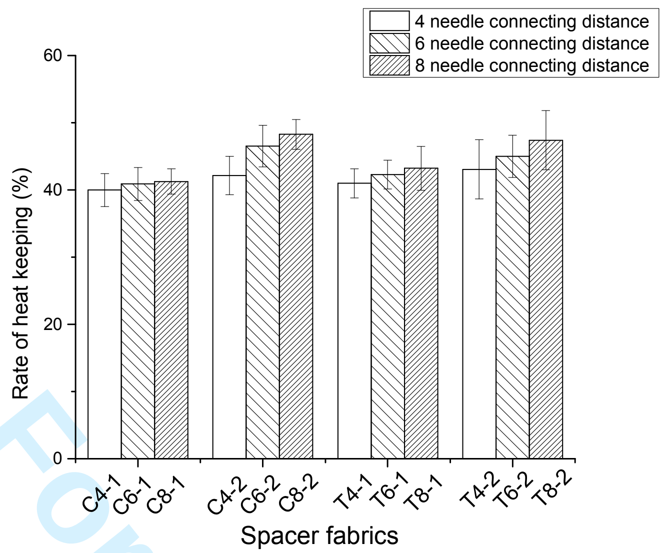


Figure 9. Rate of thermal property.

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 and T4-1 have the highest air permeability in cotton-yarn and Tencel-yarn spacer fabrics, respectively. The good air permeability is beneficial to prevent the wound malodor. Their WVTR is below 1000 g/(24h*m^2), which is lower than that of the foam dressing (around 1000 g/(24h*m^2)) [41] and that of the hydrogel dressing (about 2600 g/(24h*m^2)) [42]. This indicates that spacer fabrics C4-1 and T4-1 can create moist environments for exuding wounds. Meanwhile their thickness is the lowest in all the produced spacer fabrics, which makes them more suitable for being used as light wound dressings. The wettability and absorbency of spacer fabrics C4-1 and T4-1 were not the highest, but they can meet the requirements of absorbent dressings. By these considerations, spacer fabrics C4-1 and T4-1 were selected as the basic material of absorbent wound dressing for the further study.

Conclusions

In this study, absorbent dressings made of spacer fabrics were designed and fabricated to manage the moist environment for wound healing. 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, the following conclusions can be drawn.

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.

In summary, all the spacer fabrics produced in this study were highly absorbent and air permeable. Considering their good air permeability and appropriate absorbency and WVTR, spacer fabrics C4-1 and T4-1 were selected as the basic material of designed dressing. They would be covered with a layer of nanofibrous membrane on their outer layer surface to form the final wound dressings which will be presented in Part II.

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Response to Reviewers' Comments

(Manuscript ID TRJ-16-0056)

Dear Editor and Reviewers,

Thank you for your email on 11 May 2016 concerning reviewers' comments on this manuscript (TRJ-16-0056). We have revised our research paper according to the comments. In the revised version, the inappropriate expressions have been changed and the reasons for selection have been modified. We hope the revised manuscript and our responses to Reviewers' Comments will meet your requirements and expectations.

Response to Reviewer 1's Comments

Comments 1*:* Page 12- Line 51:"However, the type of spacer yarns had little effect on the WVTR (p = 0.1092)". p=0.1092 means the type of spacer yarns had no effect on the WVTR. Please change it.
Response*:* Thanks for identifying these problems. The incorrect expression has been changed.

Comment 2*:* The reasons of selecting C4-1 and T4-1 samples for further study should be explained more detail.
Response*:* Thanks for his/her comments. The more detailed explanation of the selection reasons has been added in the revised version.

Comment 3*:* There is a problem at reference 38.
Response*:* Thanks for identifying this problem. The mistake has been corrected.