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Spacer fabric based exuding wound dressing - Part II: Comparison with commercial wound dressings

Abstract: In this study, a three-layered composite structure based on spacer fabric was designed for absorbent wound dressing. The fabrication and selection of spacer fabrics had been discussed in Part I. In this part, two selected spacer fabrics were further modified by covering a polyurethane or a polystyrene electrospun nanofibrous membrane onto their outer layer surface to form the final spacer fabric based dressing products. In order to confirm the performance of these new spacer fabric based dressings, the comparisons were conducted with three types of commercial wound dressings. The comparison indicators included water contact angle, wettability, absorbency, air permeability and water vapor transmission rate. The results showed that in addition to very good water vapor and air permeability, the developed spacer fabric based dressings had better absorbing properties than commercial foam dressings. Furthermore, their wettability was also good for applying as wound dressings. The study has paved a new way to produce advanced wound dressings using 3D textile structures.

Keywords

spacer fabric, wound dressing, absorbent dressing, electrospun nanofibrous membrane, exuding wound.

Introduction

A composite structure for wound dressing has been designed in Part I. The structure was designed as a three-layered one which includes a hydrophobic wound contact layer, an absorbent middle layer and a waterproof outer layer. In Part I, the spacer fabric structure, which is used as the backbone of the composite wound dressing, was fabricated and selected. In this part, the final spacer fabric based dressings will be obtained by covering a layer of electrospun nanofibrous membrane on their outer layer surface to increase their waterproof property. As the spacer fabric based dressings aim to apply for exuding wounds, a comparison with similar products on the market is necessary.

Dressings are classified according to the types of wound and wound management in order to meet different applications¹⁻³. The dressings developed in this study are mainly used in the exuding period of wound healing process. 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 bradykinin⁴⁻⁷. The main component of exudate is water, but it also contains electrolytes, nutrients, proteins, inflammatory mediators, proteases, growth factors and waste products, as well as white blood cells^{3, 8, 9}. An excessive exuding wound may prevent cell proliferation and lead to maceration and excoriation of skin⁹. Thus, the main task for an absorbent dressing is to reduce exudate level.

Traditionally, cotton gauzes are applied to dressings because they are soft and flexible and have good absorption property. However, cotton gauzes allow moisture to evaporate from the wounds, making them dry without maintaining a moist environment for facilitating wound healing. In addition, cotton

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3 gauzes are easily to adhere to the wound and require frequent changes, causing trauma and pain to
4 the patients ¹⁰⁻¹². For heavy exudate wounds, foam dressings and alginate dressings are often used
5 because they are highly absorbent. Foam dressings are generally made from hydrophilic polyurethane
6 (PU) foam and have different absorption rates depending on their composition and thickness ¹³.
7 Highly absorbent foams may reduce the frequency of dressing change. Some absorption **capacities**
8 can be up to 7 days ¹⁴. Mixed cell foam with increased speed of fluid uptake provides cushioning and
9 protection, and fast absorption and vertical wicking to reduce risk of maceration to the adjacent tissue.
10 Nonetheless, the prices of commercial foam dressings are very expensive, usually dozens of times
11 higher than normal cotton gauze, which limits their utilization, especially in developing areas ¹⁵.
12 Alginate wound dressings are non-woven materials made of soft fibers derived from brown seaweed.
13 When placed within the wound bed, alginate dressings react with serum and exudate via exchanging
14 sodium ions with calcium ions exuded from the wound ¹⁶. The ion exchange with exudate forms a
15 fibrous gel, which can provide a moist and warm wound environment. As alginates are highly
16 permeable and non-occlusive, a secondary dressing is normally required. The most commonly used
17 secondary dressing is gauze ¹⁷⁻¹⁹. However, a majority of alginate dressings may trap bacteria, often
18 giving rise to wound malodor and bringing unpleasant experience to patients.

19
20 The main limitations of the currently available dressings for heavy exudate wounds can be
21 summarized as follows ^{3, 4, 20-22}: (i) The majority of high absorbent dressings are made of foams,
22 alginate, hydrogel, hydrocolloid, etc., and cannot retain their original shape or integrity during the
23 use. Therefore, cleaning or washing to remove the remnants of such dressings left in the wound is
24 required ²³; (ii) Wound malodor is partially caused by heat generation from skins and poor air
25 permeability; (iii) Low extensibility reduces the comfort when applied to a joint or a region of
26 movement of the body; (iv) Limited shapes and sizes lead to dressing fit less compactly; (v) Some of
27 them are adherent to the wound, causing trauma and pain on removal; (vi) The costs involved are
28 high.

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30 Although some compression bandages were developed based on spacer fabrics, little application for
31 absorbent dressings using spacer fabrics have been reported. A multilayer compression bandage was
32 developed according to literature ²⁴. It consists of an inner wound facing layer which comprises a knit
33 made of bacteriostatic viscose yarns; an intermediate layer ²⁵ providing an auxetic effect; an outer
34 layer coated with adhesive. This three-layered structure, however, is separated instead of integrity
35 like spacer fabric. In addition, some applications of spacer fabrics as absorbent medical bandage or
36 wound dressing only focused on the absorbency, rather than moisture management and having a
37 protective outer surface ^{26, 27}.

38
39 In Part I, a new type of wound dressings based on spacer fabric structure has been proposed, and
40 spacer fabrics which could provide a moist environment to accelerate wound healing and could offer
41 good permeability to avoid malodor and maceration have been fabricated **due to their**
42 **three-dimensional structure**. As a wound dressing performs like a skin to prevent contaminated fluid
43 and harmful substance to have access to the wound, its protective function against water and other
44 fluids is also required. Making the outer layer of a dressing to be waterproof can meet this
45 requirement. Although waterproof products have been surveyed for many years, a great amount of
46 them, especially waterproof coatings, are non-permeable or have very low air and water vapor
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transmission²⁸.

It is found that electrospun nanofibrous membrane formed by electrospinning process can be highly permeable due to their special fibrous structures. The polystyrene (PS) nanofibrous materials have been reported to be superhydrophobic²⁹. They can be a substitute for fluorochemical water resistant agents. A number of investigations on the electrospinning of PS have been conducted. Zheng³⁰ et al. found that the water contact values of electrospinning PS surfaces were in the range of 140°-160°, varying with the fiber structures. Kang²⁹ et al. prepared the electrospun fibers from PS solutions made with several solvents, including THF, chloroform and DMF, and the water contact angle of the PS film could reach 152°. In addition, PU materials are also water resistant. The PU coated permeable textile generated had the waterproof higher than 10,000 mm H₂O and the water vapor permeability higher than 900 g/(m² × 24 h)³¹. The effects of concentration and instrument parameters on the morphology and diameter of electrospun PU were investigated in detail³². As PU foams are often used as wound dressings, they are a kind of medical material without toxicity. Since water resistant surfaces with high water contact angles could be obtained by using PU and PS electrospun nanofibrous membranes, these two types of membranes were selected for covering on the surfaces of the spacer fabrics to prevent wounds from contaminated fluids in this study. Therefore, in Part II, the spacer fabrics selected in Part I were first modified by covering a PS or PU electrospun nanofibrous membrane to form the final spacer fabric based dressings with improved waterproof function. Then, the obtained spacer fabric based dressings were compared with commercial highly absorbent dressings to confirm the feasibility of using spacer fabric based dressing to replace currently used foam based and alginate dressings. As the electrospinning processes of PU and PS had been investigated in numbers of previous studies, our study was mainly focused on the properties of designed wound dressings, instead of the electrospinning processes of PU and PS.

Materials and methods

Fabrication of electrospun nanofibrous membranes

Two kinds of spacer fabrics C4-1 and T4-1 have been selected in Part I of this study. These fabrics were produced by using a single polyester/spandex (100D/40D) yarn to knit the two outer layers, and a 32S/2 bleached cotton or Tencel yarn to knit the spacer layer with a connecting distance of 4 needles, respectively. After knitting, the spacer fabrics were steamed and then conditioned at 20 °C and 65% RH for a week. As mentioned above, PU and PS were selected for covering nanofibrous membranes onto their outer layer surfaces, respectively. While the wt 20% PS electrospinning solution was prepared by dissolving 20g PS (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 wt 11% PU electrospinning solution was prepared by dissolving 10g PU (average Mw ~ 600,000, purchased from Hong Kong Hi-Tech Enterprises Ltd.) in 90g DMF. The fabrication process of nanofibrous membrane on a spacer fabric is schematically shown in Figure 1. It was performed on an electrospinning apparatus purchased from Micro & Technologies Expert (TL-Pro), Shenzhen, China. As shown in Figure 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 PS was sprayed for 30 min, and the PU was sprayed for 1h. The PS or PU nanofibers were connected 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 °C and 65 RH%. After completing the electrospinning process, the nanofibrous membrane covered on the spacer fabric was air-dried for about 24h. Combining two types of materials PU and PS, and two spacer fabrics C4-1 and T4-1, four different spacer fabric based dressings were obtained. They were named as Dressing A (C4-1 covered with PS membrane), Dressing B (C4-1 covered with PU membrane), Dressing C (T4-1 covered with PS membrane) and Dressing D (T4-1 covered with PU membrane). Because the thickness and weight of electrospun nanofibrous membrane could be negligible, the thickness and areal mass of dressing A and B were the same as those of spacer fabric C4-1, which were 3.253 mm and 540.4 g/m² respectively, and the thickness and areal mass of dressing C and D were the same as those of spacer fabric T4-1, which were 3.343 mm and 616.4 g/m², respectively.

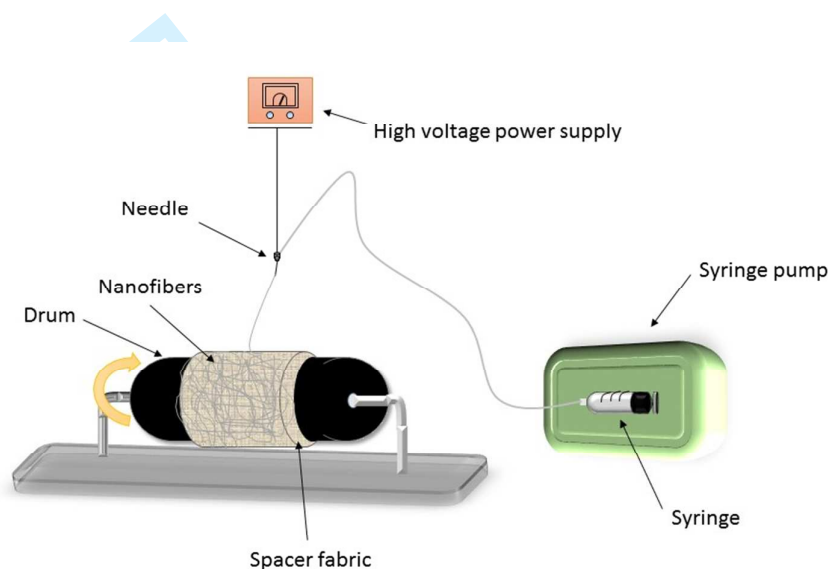


Figure 1. Fabrication process of electrospun nanofibrous membrane on spacer fabric.

Characterization of electrospun nanofiber membranes

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

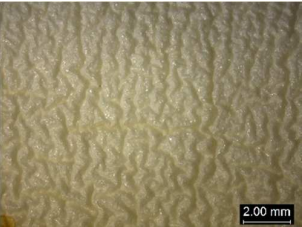



The morphologies of electrospun nanofibrous membranes were observed by field emission scanning electron microscopy (FE-SEM) on a Jeol 6490 microscope. Prior to observation, samples were fixed on the sample stage using an electroconductive double-tape and then a layer of gold was sputtered on the surface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

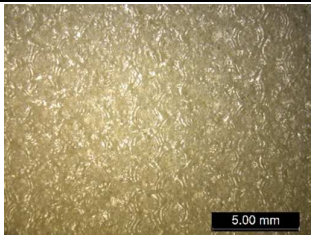
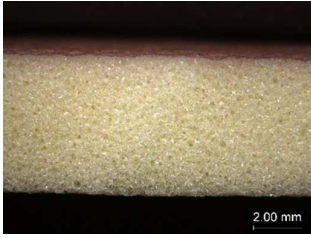


Comparison with commercial wound dressings

In order to confirm the performance of the spacer fabric based dressings developed, a comparison was conducted with three types of commercial dressings for heavily exudate wounds, Foam A, Foam B and Alginate. The details and photos of these commercial dressings are shown in Table 1 and

Figure 2, respectively. Foam A was a soft and conformable PU foam dressing that could effectively absorb and retain wound exudate. It ensured an optimal moisture balance for healing of exuding wounds. Foam B was a type of hydrocellular foam dressing. 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 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 make patients uncomfortable.

Table 1. Details of the commercial wound dressings.

Type	Base material	Product name & Brand	Size	Areal mass (g/m ²)	Thickness (mm)	Surfaces and cross-sections
Foam A	Hydrophilic PU foam	Biatain non-adhesive foam dressing from Coloplast	10 cm × 10 cm	754 (± 23.1)	4.65 (± 0.06)	 <p>Outer layer</p>  <p>Wound contact layer</p>  <p>Cross-section</p>
Foam B	Hydrocellular PU foam	Allevyn non-adhesive foam dressing from smith & nephew	10 cm × 10 cm	680 (± 14.2)	5.70 (± 0.05)	 <p>Outer layer</p>

						 <p>Wound contact layer</p>  <p>Cross-section</p>
Alginate	Calcium alginate	Algisite from smith & nephew	10 cm × 10 cm	136 (± 6.5)	2.28 (± 0.02)	 <p>Surface (two surfaces are the same)</p>  <p>Cross-section</p>

Note: Standard deviations are given in parentheses.

The following performance indicators were used for the comparisons between the spacer fabric based dressings and commercial products. They are water contact angle, wettability, absorbency, air permeability and water vapor transmission rate (WVTR). When applying to wounds, dressings should be water resistant in their outer layer, and should absorb liquid quickly from the wound contact layer. While the water contact angle of the outer layer of a dressing defines its ability to preserve wound from contaminated fluids, the wettability indicates the time needed for fluid to go through the wound inner contact layer. Absorbency shows the capacity of dressings for liquid retention, which presents the exudate absorptive capacity. Besides, water vapor transmission defines the capacity of moist management. Since a moisture environment is beneficial to wound healing, the WVTR is a crucial index for moisture maintaining property. Air permeability shows breathability of dressings. Except the water contact angle, the testing conditions and methods for wettability and air permeability were maintained the same as used in Part I. Conditions were modified for absorbency and WVTR tests considering real applications of dressings. All the samples were conditioned for 24h

and all the tests **except the absorbency tests** which were carried out at 20 °C and 65% RH.

Water contact angle test. Water contact angle tests were carried out on the outer layer surface of dressings using contact angle system OCA (Data Physics, Germany). A drop of 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 in the three time points for each specimen. Five specimens were used for each type of dressings.

Wettability test. Wetting time of dressings was measured on the wound contact layer according to AATCC 79 method, which was detailed in Part I.

Absorbency test. For the comparison of dressings, the liquid containing Na⁺ and Ca²⁺ ions was used to replace the distilled water in absorbency test 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 (25cm²) sample was first put in a warmed solution (37 °C) having 40 times of the mass of dressing, and then transferred to an oven to stand for 30 min at 37 °C and finally drained for 30s. Five specimens were tested for each type of fabrics and dressings. The absorbency was calculated according to Formula (1).

$$\text{Absorbency (g/100cm}^2\text{)} = (W_1 - W_0)/25 \times 100 \quad (1)$$

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

Air permeability test. The air permeability testing method of wound dressings was the same as described in Part I 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/cm² and 0.020 ml/s/cm² at 100Pa, respectively.

Water vapor transmission rate (WVTR) test. The WVTR tests of dressings were carried out according to the same method as presented in Part I, according to British Standard 7209. However, in addition to dry samples, wet samples were also tested for comparison. While the dry samples were obtained by keeping them in an environment of 20 °C and 65 RH% for 24h, the wet samples were prepared by first immersing the dry samples into distilled water for 10 min and then draining for 30 s. During the WVTR test, the wound contact layers of samples were placed downward to face the water level in dishes.

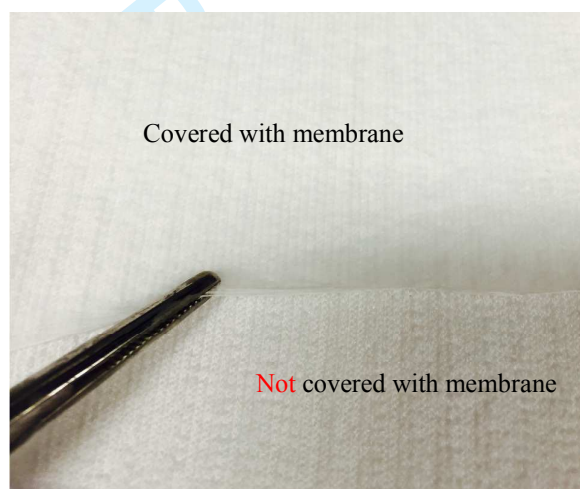
Results and Discussion

Structures and morphologies of PS and PU nanofibrous membranes

PS and PU solution **were** treated onto the surface of spacer fabrics by electrospinning method to form the designed dressings. As shown in Figure 2, a continuous membrane was formed and covered on

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3 the outer layer surface of spacer fabric. FT-IR spectra of PS and PU nanofibrous membranes are
4 shown in Figure 3. In the FT-IR spectra of PS, the absorption bands at 2922 and 2852 cm^{-1} were the
5 asymmetric and symmetric stretching vibrations of $-\text{CH}_2$. The peaks at 1492 and 1452 may result
6 from the vibration of C-C of the benzene ring. The absorption bands in 690 ~ 790 cm^{-1} region are
7 caused by C-H of benzene ring. In the FT-IR spectra of PU, a strong absorbing peak appears at
8 1729.26 cm^{-1} owing to the stretching vibration of C=O bond in carbamate (R-NH-C(=O)-O-R). There
9 was a peak at 1703.49 cm^{-1} attributed to C=O stretch of amido ester. The wide 1105 ~ 1066 cm^{-1}
10 region was caused by the C-O-C asymmetrical flexing vibration.
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14 The SEM images of the PS and PU nanofibrous membranes are shown in Figure 4. It can be seen that
15 nanofibers were interlaced together. The diameters of PS nanofibers were bigger than 2 μm . They
16 were large but were distributed evenly. PU nanofibers were fine with diameters less than 1 μm . The
17 PU nanofibers were not uniform in their diameter, because the viscosity of PU solution and the
18 electrospun voltage (15 kV) were relatively high. However, no obvious beads and beaded nanofibers
19 were found in both types of membranes. The denser structure of PU membrane made its air
20 permeability lower than PS membrane.
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41 Figure 2. Covering of electrospun nanofibrous membrane onto spacer fabric.
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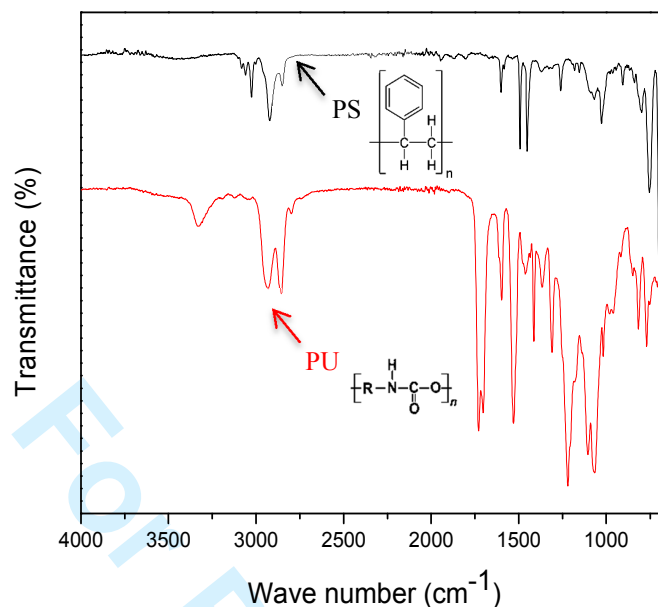


Figure 3. FT-IR spectra of PS and PU electrospun nanofibrous membrane.

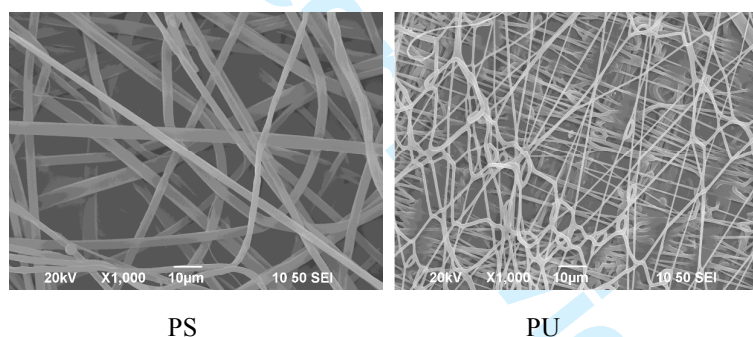


Figure 4. SEM images of PS and PU electrospun nanofibrous membranes.

Water contact angle

The water contact angles of the dressings are shown in Figure 5. The images of water drops contacting with dressings after 0s, 10s, 30s are presented in Figure 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, all the spacer fabric based dressings had much larger 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 120° . Alginate dressing is an absorbent without hydrophobic surface, and therefore the drop of water spread out immediately. As shown in Figure 6, the water contact angles of the spacer fabric based dressings decreased slower than those of the foam dressings. Especially, the contact angles of dressing A and C (covered with PS nanofibrous membrane) changed little after 30s, which indicated that PS nanofibrous membrane had very good water resistance. Dressing B and D,

covered with PU nanofibrous membrane, had inferior waterproof property comparing with dressing A and C, but they still had much better water resistance than foam dressings and alginate dressing. It is also found that dressings A and B (made of cotton spacer yarns) had slightly higher water contact angles than dressings C and D (made of Tencel spacer yarns), respectively.

When water dropped on the surface of spacer fabric based dressing, 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 2), the water contact angle was mainly determined by the membrane. Surface energy and surface roughness are the dominant factors for water resistance³⁰. Since both the PS and PU membranes were obtained by electrospinning, their morphology was nanofibers, which means that their surface roughness was similar. Therefore, the reason for PS membrane had better water resistance than PU membrane is that the surface energy of PS membrane is lower than PU membrane, which is determined by the chemical groups. According to the chemical formula shown in Figure 3, PS has benzene ring in its structure, whereas PU has no benzene ring but carbamate instead. These different chemical groups lead to the difference of water contact angles between PS and PU 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. The different distribution of nanofibers on cotton spacer-yarn fabrics and Tencel spacer-yarn fabrics led to slightly difference of the water resistance. 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.

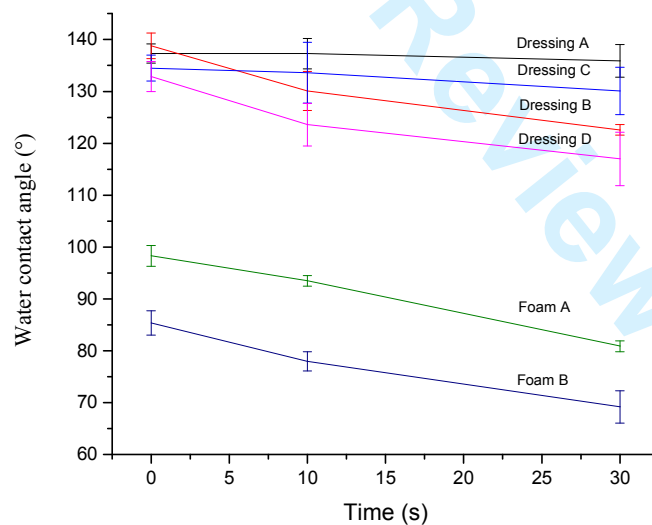
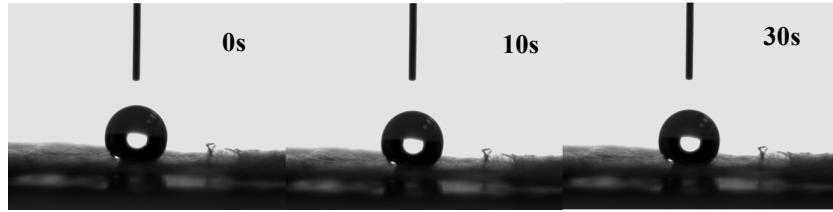
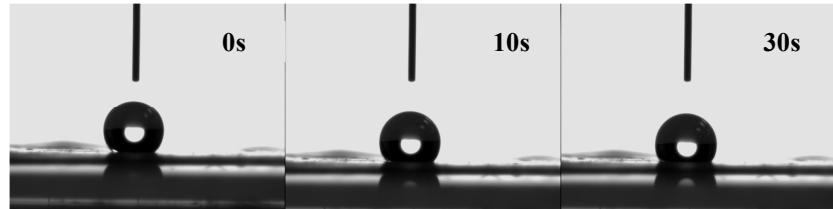


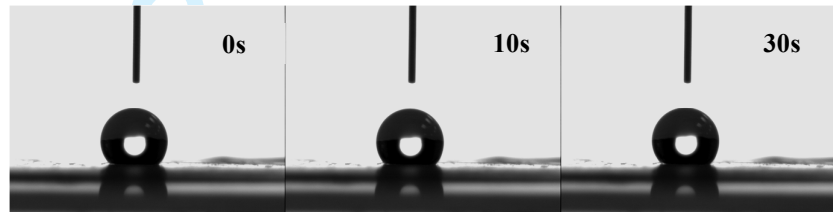
Figure 5. Water contact angles of dressings.



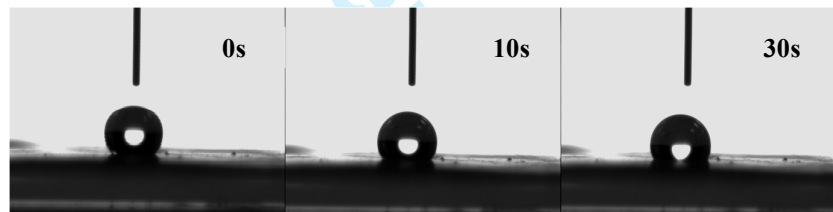
(a) Dressing A



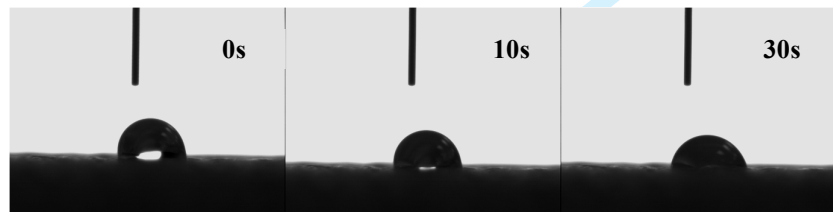
(b) Dressing B



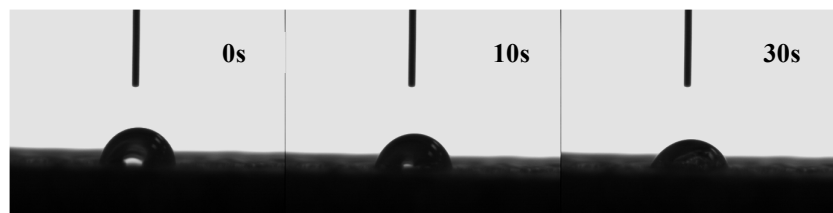
(c) Dressing C



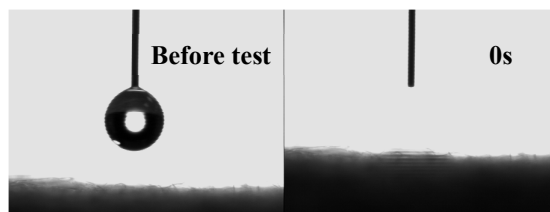
(d) Dressing D



(e) Foam A



(f) Foam B



(g) Alginate

Figure 6. Images of water drops contacting with dressings after 0s, 10s and 30s.

Wettability

The wetting times of the spacer fabric based dressings and commercial dressings are shown in Figure 7. 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. 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 is made from hydrocellular PU foam, there is a non-adherent film on its wound contact layer (Table 1). The non-adherent film lowers the adherence and reduces the pain while removing the dressing, but it also blocks liquid to entry into the dressing directly. Foam A is also made of PU foam, but its wetting time was much shorter than Foam B, because no film covers on the wound contact layer of Foam A. The wetting time of Alginate was the shortest, because its main ingredient calcium alginate is a type of salts. So water could spread on the surface quickly and lose its reflectivity directly while contacted.

The wetting time of the spacer fabric based dressing mainly depends on the type of spacer yarns. Because Tencel spacer yarn absorbed water very fast, the wetting time of dressing C and D were quite short (around 1 second). As the wettability was tested on the wound contact layer of the spacer fabric based dressings, the effect of electrospun fibrous membrane was very low. The wettability of dressing A and B 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. The results show that the wettability of spacer fabric based dressings C and D was much better than that of foam dressings.

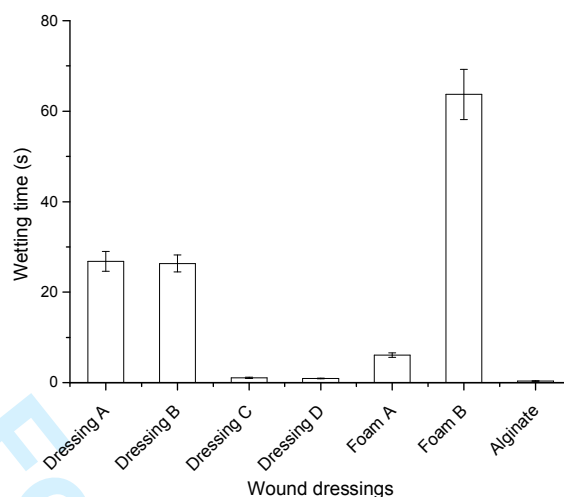


Figure 7. Wetting time of wound contact layer of wound dressings.

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

Figure 8 shows the absorbency of liquid containing Na^+ and Ca^{2+} ions of all the dressings. 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 fabric based dressings was higher than 3.3 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 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 PU foams. Hydrophilic PU foam was produced by grafting hydrophilic compounds on the PU 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 PU 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 based dressings, their absorbency was better than that of Foam B and Alginate. It is noticed that although dressing C and D absorbed liquid faster than dressing A and B, dressing A and B could lock more ionic solution within its structure than dressing C and D. This result was consistent with water absorbency of spacer fabrics. Although Tencel spacer yarn absorbs liquid faster than cotton spacer yarn, the cotton yarn could retain more liquid inside the spacer fabric based dressing. The large amount of liquid absorption extends the dressing period and reduces the frequency of dressing change. Furthermore, all extrudes emitted from the wound should be entirely absorbed by the dressing and liquid retention sustains a moist environment for wound healing.

Consequently, the spacer fabric based dressings were competent to be used as absorbent dressings for exuding wounds.

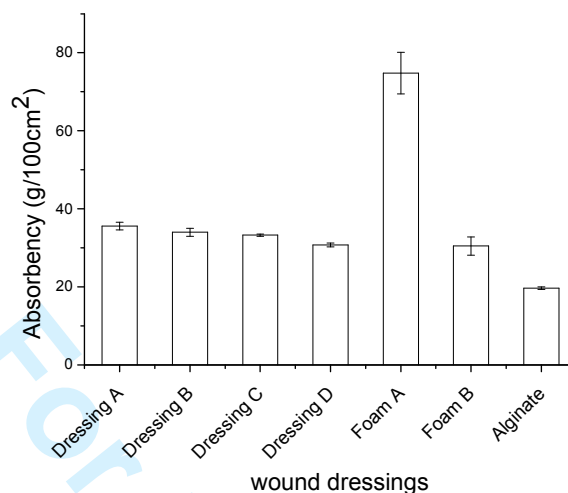


Figure 8. Absorbency of liquid containing Na⁺ and Ca²⁺ ions of wound dressings.

Air permeability

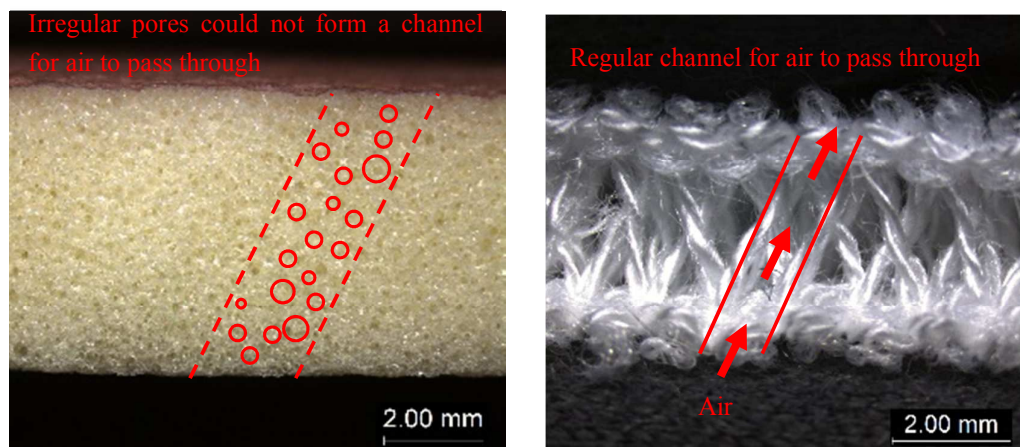
The testing results of air permeability of all the dressings are presented in Table 2. It can be seen that the air permeability values of Foam A and Foam B were smaller than 0.020 ml/s/cm² at 100Pa, exceeding the minimum value that SDL M021S tester could measure. This implicates that the air permeability of Foam A and Foam B was very poor. As shown in Figure 9(a), the foam dressings are quite thick. They were made from dense PU foams with a few small irregular pores inside. It is difficult for air to pass through the PU matrix. In addition, the non-adherent film on the surface of Foam B further reduces 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/cm² at 100Pa. However, too high air permeability of Alginate makes it a non-occlusive dressing. In this case, a secondary dressing is required, and the most commonly used secondary dressing is gauze.

Table 2. Air permeability of wound dressings.

Sample code	Air permeability (ml/s/cm ² at 100Pa)
Dressing A	21.260 (± 0.574)
Dressing B	20.118 (± 0.906)
Dressing C	31.890 (± 1.710)
Dressing D	29.370 (± 2.181)
Foam A	< 0.020
Foam B	< 0.020

Alginate	> 78.740
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Note: Standard deviations are given in parentheses.



(a) Foam dressing

(b) Spacer fabric based dressings

Figure 9. 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 9, the spacer fabric based dressings consisted of repeating units, and these regular units generated regular channels (Figure 9b) rather than irregular structure of PU matrix (Figure 9a). The openings regularly arranged in a spacer fabric structure can reduce air resistance and facilitate air circulation. On the contrary, the small pores irregularly arranged in a foam structure cannot 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 electrospun nanofibrous membrane could reduce their air permeability. As shown in Table 3, dressing A and B (both fabricated with spacer fabric C4-1) had lower air permeability than dressing C and D (both fabricated with spacer fabric T 4-1). This is caused by the air resistance property of cotton and Tencel spacer yarns. As explained in Part I, the fine hairs on the cotton fiber made air difficult to pass through, while the surface of Tencel fiber was smooth, which facilitated air to pass through. As for the dressings made of the same base spacer fabric, the air permeability of dressing A (C4-1 covered with PS) was higher than that of dressing B (C4-1 covered with PU), and the air permeability of dressing C (T 4-1 covered with PS) was higher air than that of dressing D (T 4-1 covered with PU). This indicates that air permeability of PS electrospun nanofibrous membrane was better than that of PU membrane, because the structure of PU membrane was denser than that of PS membrane (Figure 4).

Anaerobic bacteria are one of the main causes for wound malodor when severe colonization or infection happens. Air permeable wound dressing allows oxygen in and contact with the wound. As a result, the amount of anaerobic bacteria can be reduced and the wound malodor can be eased.

However, it is hard to make a material to have good air permeability and good water resistance at the same time. Most of wound dressing materials have good air permeability but poor water resistance, such as Alginate; or have good waterproof but poor air permeability, such as foam dressings. The combination of spacer fabrics and electrospun nanofibrous membrane has provided a good solution to this difficult problem. The spacer fabric based dressings had quite good air permeability and very good waterproof. Therefore, they were suitable for applying as wound dressings.

Water vapor permeability

The results of the WVTR of the dry dressings are shown in Figure 10. As the same as the air permeability, foam dressings had the lowest water vapor permeability. This is also due to their high density and irregular pores of PU matrix. As quoted in Part I, low WVTR may cause skin maceration and even infection, so that the WVTR of wound dressings is suggested to be higher than that of normal skin, which is 200-500 g/(24h*m²). From Figure 10, the WVTR of Foam B was lower than 500 g/(24h*m²), while the WVTR of Foam A was around 550 g/(24h*m²). There is a bigger chance for patients who are using foam dressings to get skin maceration or infection.

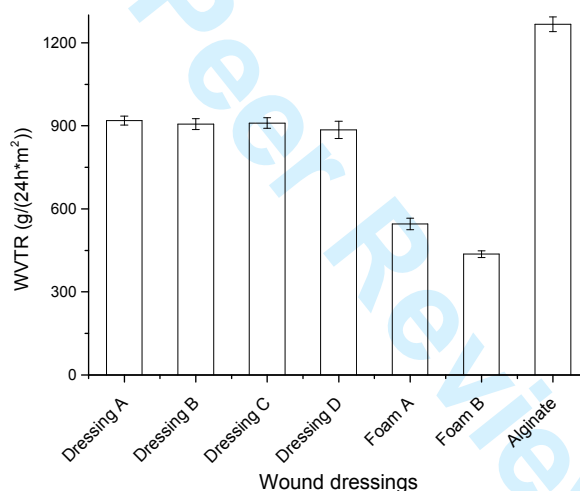


Figure 10. WVTR of dry wound dressings.

Alginate dressing is highly permeable for water vapor with a WVTR of 1267 g/(24h*m²). It was made from calcium alginate fibers by nonwoven technology. As the nonwoven structure was very loose and the thickness of Alginate dressing was low, Alginate dressing had a very high permeability. However, high permeability may cause too much evaporation and make the wound dressing hardly to keep a required moisture environment for wound healing. For Alginate, the gauze secondary dressing is required in most situations.

The WVTR of all the spacer fabric based dressings was around 900 g/(24h*m²), between the foam dressings and alginate dressing. On one hand, the WVTR of the spacer fabric based dressings was higher than that of foam dressings because of the similar reason as air permeability. The lower density and regular channels in spacer fabric based dressings were beneficial to the transmission of

water vapor. On the other hand, the WVTR of spacer fabric based dressings was much lower than that of Alginate. This is due to their higher thickness, and also the covering of the electrospun nanofibrous membrane on their surfaces. The membrane was not only waterproof, but also permeable for air and water vapor.

A material with a high rate of water vapor transmission can transport extrude or sweat from the surrounding skin in order to maintain ventilation. It helps to minimize the risk of maceration and infection to the wound and tissue. At the same time, keeping a moist environment for wound to avoid escharosis and to accelerate wound healing needs relatively low WVTR. In other words, it should not be a non-occlusive dressing like Alginate if no secondary dressing will be used. In this regard, the combination of absorbent spacer fabric and waterproof and permeable membrane brought many benefits to wound healing.

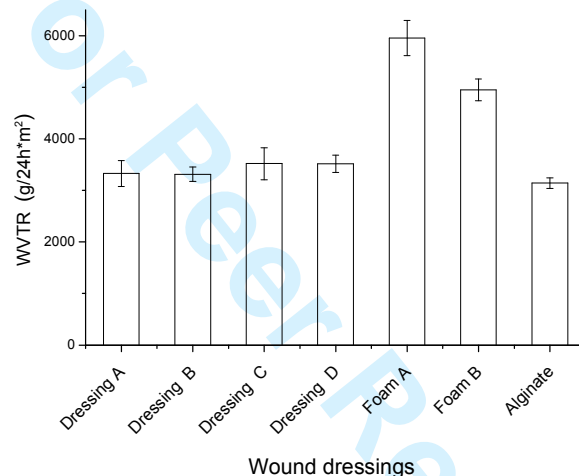


Figure 11. WVTR of wet wound dressings.

The testing results of the WVTR of the wet wound dressings are presented in Figure 11. Contrary to the dry condition, the foam dressings had the highest WVTR, and the WVTR of spacer fabric based dressings was lower. There are two reasons. The first one is that Foam A could absorb more water (Figure 8) than spacer fabric based dressings in the same period of time, which means that more water was exposed in the air for evaporation. However, Foam B absorbed similar amount of water (Figure 8) but transmit more water vapor than spacer fabric based dressings under wet condition. This may be explained by the second reason that the specific area of PU foam was much larger than that of cotton or Tencel fibers. Materials with larger specific area are easier to cause evaporation after absorbing.

When being applied on an exuding wound, a dressing should absorb exudates and blood fast. The dressing would become wet in a short period. So the low WVTR in wet condition is necessary and important because fluid inside a dressing has great effects on water vapor permeability and moist healing environment. According to this point, the spacer fabric based dressings had an advantage in keeping a moist environment for wound, which is the most important thing for an absorbent dressing.

Conclusions

In this part, the four spacer fabric based dressings were obtained by covering a PS or PU electrospun nanofibrous membrane on the outer layer surface of spacer fabrics and compared with three types of commercial dressing products based on different performance indicators. FT-IR and SEM apparatus were used to examine the structures of PS and PU membranes. From the results obtained, it can be concluded that the water resistance of the spacer fabric based dressings was better than that of the commercial dressings. At the same time, their air permeability was also much better than that of the foam dressings. Regarding the absorbency of liquid containing Na^+ and Ca^{2+} ions, the spacer fabric based dressings were competence to the commercial dressings. Although the WVTR of spacer fabric based dressings in dry condition were higher than the foam dressings, their WVTR in wet condition were lower than the foam dressings. Between the dressings made of the same spacer fabrics, the PS membrane had better water resistance and lower air resistance than the PU membrane. Although the spacer fabric based dressings made of cotton spacer yarns required longer wetting time than the dressings made of Tencel spacer yarns, they could maintain more liquid inside their spacer layer. The spacer fabric based dressings could absorb large amount of fluid in a short period, and they were permeable for air and water vapor while they were tend to keep a moist environment with low evaporation after absorbing. In addition, their costs were much lower than foam dressings and alginate dressing and their structures could easily be tailored to satisfy requirements for different types of wounds. In conclusion, spacer fabric based dressing can be a promising product for wound healing application.

Acknowledgements

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Response to Reviewers' Comments

(Manuscript ID TRJ-16-0055)

Dear Editor and Reviewers,

We appreciate the time and efforts by the editor and reviewers in reviewing this manuscript. The manuscript TRJ-16-0055 has been revised according to the reviewers' comments. In the revised version, the introduction part has been modified by adding reviews of related literatures. Deep discussion on the results have been added. Some errors of forms and tense were corrected. We hope the revised manuscript will meet the journal publication requirements.

Response to Reviewer 1's Comments

Comments 1-6:

1 The keywords should be rearranged according to the TRJ form.

2 Heading of sections and subsections, and reference numbers should be written according to TRJ form.

3 There should be dots after table and figure titles, such as Figure 1. and Table 1., and also after the all sentence.

4 It would be better to use "Surface and cross-sectional images of the commercial wound dressings" instead of "Photos of commercial dressing".

5 Page 6 row 14 and page 7 row 6: the typos of 20 oC should be corrected.

6 The author should rearrange the Reference section according to TRJ form.

Response: Thanks for identify these problems. The incorrect forms have been changed to right forms. The figure title has been changed according to the comments. The symbol has been corrected.

Response to Reviewer 2's Comments

Comment 1: Author did not gave the details about sample C4-1 and T4-1. It is required.

Response: Thanks for pointing out this problem. A paragraph was added in the "Fabrication of electrospun nanofibrous membranes" section to briefly introduce the fabrication about sample C4-1 and T4-1.

Comment 2: Author mentioned disadvantages of cotton based gauze fabrics in "Introduction" part. Still the author selected Cotton for sample (C4-1). Why?

Response: Thanks for raising this question. Generally, cotton gauzes allow moisture to evaporate from the wounds, making them dry without maintaining the moist environment to facilitate wound healing. This is the main limitation of cotton gauzes. However, as mentioned in the second last paragraph of introduction part, spacer fabric based dressings can absorb and retain liquid inside their body to provide a moist healing environment and accelerate wound healing. The reason is that the advantageous structures of spacer fabrics can store moisture. In addition, by keeping a moist environment, spacer fabric based wound dressings can lower the adherence and reduce pain.

Comment 3: Author has conducted several comfort related tests on developed samples. But the reason for conducting the tests are missing. In method section, author should clearly mention the relevance of that

particular test in this context.

Response: Thanks for reviewer's comment. Required reasons for conducting the tests were added in the second paragraph of "Comparison with commercial wound dressings" section. Combining with the original contents, the reasons to select these tests were explained.

Response to Reviewer 3's Comments

General comments: The paper has a very interesting topic and the writers investigated many different parameters. However, they only concluded what they found from the tests. No knowledge could be found from the text about why they obtained these results. The results must be deeply discussed.

Response: Authors are grateful for the reviewer's positive comments. Reasons for conducting the tests have been added in the second paragraph of "Comparison with commercial wound dressings" section. Reasons for selecting PU and PS as water resistant materials have also been added in the paper. The discussion has also provided according to the following comments, including the difference between the water contact angles of PU and PS dressings and the effect of Tencel or cotton on the final contact angle.

Comment 1: Are there any study related to combination of foam and spacer fabric?

Response: Thanks for raising this question. The combination of foam and spacer fabric was reported in some literatures. The 3D spacer fabrics filled with PU foams were also investigated by various researchers. However, most of the investigations focused on the mechanical properties, such as compression, stiffness and cushion properties. The foam filled spacer fabric composites often applied as sound absorbent, flame retardant and reinforce building materials. Composites made of foam and spacer fabric were not reported as medical materials.

Comment 2: Why did you selected PU and PS for the study?

Response: Thanks for raising this question. The reasons for selecting PU and PS have been added in the last paragraph of introduction part. The main reason is that water resistant surfaces with high water contact angle can be produced by using these types of materials. In addition, the electrospinning processes of PU and PS were investigated in detail in numbers of previous studies. In this study, we mainly focused on the properties of designed wound dressings, instead of the electrospinning processes of PU and PS. So PU and PS were selected for this study.

Comment 3: Dressings should be given in a Table.

Response: Thanks for reviewer's advice. The images of wound dressings were moved in Table 1.

Comment 4: Although, the reader can found the information about C1 and T1 from part 1, it is better to give fabric information in Part 2 again.

Response: Thanks for pointing out this problem. A paragraph has been added in the "Fabrication of electrospun nanofibrous membranes" section to briefly introduce the fabrication about sample C4-1 and T4-1.

Comment 5: What makes the difference between the water contact angles of PU and PS dressings?

Response: Thanks for rising this question. Surface energy and surface roughness are the dominant factors for water resistance. Since both of PS and PU membranes were obtained by electrospinning, their

1
2
3 morphology was nanofibers, which means their surface roughness was similar. Therefore, the reason for
4 PS membrane had better water resistance than PU membrane was that the surface energy of PS membrane
5 was lower than PU membrane, which was determined by the chemical groups. The explanation has been
6 added in the “water contact angle” section.
7
8

9
10 **Comment 6:** What is the effect of Tencel or cotton on the final contact angle? Why?

11 **Response:** Thanks for rising this question. As this membrane was continuously covered on the surface of
12 spacer fabric (as shown in Figure 2), the water contact angle was mainly determined by the membrane. The
13 spacer yarns slightly affected the water resistance, as the tuck loops appearing on the spacer fabric surface
14 influenced the uniformity of membranes. The different distribution of nanofibers on cotton spacer-yarn
15 fabrics and Tencel spacer-yarn fabrics led to slightly difference of the water resistance.
16
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18 **Comment 7:** There must be a standar in the paper. Some results are given in a Tbale while some of them
19 given in a Table.

20 **Response:** Thanks for the advice. All the results except air permeability were presented in figures. The
21 wetting time data was rearranged in a figure. The air permeability of the foam dressings and alginate
22 dressings cannot be measured, so the data was presented in a table, such as < 0.020 or > 78.740
23 ml/s/cm^2 at 100Pa.
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