In Vitro Characterisation and Evaluation of Different Types of Wound Dressing Materials

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Abstract In recent years, textile based wound dressing products have grown from simple gauze to smart dressings with considerable technical and commercial impact. Today, wound dressings are manufactured from a large variety of different materials and applied in all phases of wound healing. In this study, commercially available wound dressing products were investigated and compared in vitro. The dressings tested and evaluated vary in their components and structures and basically fell into three main groups: nonwoven, foam and hydroactive dressing products. This study tested and analysed the properties of 13 different commercial dressings: 5 nonwoven, 5 foam and 3 hydroactive dressings. Standard test methods were employed during the study in order to determine the fluid handling capability, dehydration rate, vertical wicking, absorption behaviour and pH values of the dressings. These characteristics have profound effect on the performance of the dressings as wound care biomedical materials. It was found that the nonwoven fibrous dressings have better absorbency characteristics than foam and hydroactive dressings and the nonwoven dressings also had lower pH value compared to the foam and hydroactive dressings.

Keywords: fluid handling, gelling and swelling, in vitro, characterisation, wound dressing

1. Introduction

Wound healing is the tissue response to injury and is also the process of tissue regeneration. It is a complex biological process [1]. Inappropriate wound dressing can lead to impaired wound healing. Wound dressings research and innovation is a major stimulus to the medical textiles industry. Smart dressings are an invaluable development in wound dressing management. Over 2500 dressing products are available in a variety of generic categories and their number is continuously increasing.

An ideal wound dressing should possess many attributes, but the following properties should be consistently present: it should create a moist environment at the wound site; enables gaseous exchange; protects the wound from secondary infection; allows ongoing assessment; provides a barrier to pathogens, and be comfortable and adaptable; should be cost-effective; and be able to be removed without causing trauma [2]. A moist wound interface is essential to facilitate fibroblast proliferation and epithelialisation [3]. Modern dressings, especially fibrous dressings do not allow the wound to dry out and cause trauma, moreover they have shorter healing time as compared to the traditional dressings. Modern dressings absorb exudate more effectively and delay dressing changing time which can reduce dressing cost, infection and nursing time [4,5,6]. Modern dressings are designed to keep the wound temperature between 35-40°C, if the wound temperature is too low or too high, the wound healing time will increase due to mitotic activity [7]. Another important property of an ideal dressing is that it has to be hypoallergenic [8,9].

Other essential properties of dressing are; a) easy to use; b) adaptability and comfort; c) conformability for application to the different body parts; and d) must be effective and fast acting. Some fibrous and soft silicone foam products are able to meet the requirements of these properties. The frequency of dressing changes is also a critical factor for the patient, as well as the cost of the dressing and the trauma caused during change of a dressing. The dressing changes depend on the wound type and most of the modern dressings do not need to be changed daily, if there is no leakage or strike-through. They are generally changed from between five to seven days [10,11].

In this paper, some of the most common commercially available wound dressing products were investigated and compared in vitro. The dressings tested fell into three groups: nonwoven, foam and hydroactive dressing products. In this study 13 different commercial dressings - 5 nonwoven, 5 foam and 3 hydroactive dressings – were tested and analysed. They vary in their components and structures. Standard test methods were employed during the study in a conditioned atmosphere of 65 % rh and 20°C (ASTM D-1776-90) involving the testing of dressing mass (BS EN 12127:1998), thickness (BS EN ISO 9073-2:1997), absorbency (BS EN 13726-1), dehydration rate, vertical wicking, dispersion characteristics (BS EN 13726-2:2001, section 3.6), rate of absorption and air permeability (ASTM D737-96).

2. Materials and Methods
2.1. Materials

In this study thirteen different commercial dressings (Table 1), purchased from different wound dressing suppliers in UK, have been tested and evaluated. In order to determine the wicking properties of the dressings Test suppliers in UK, have been tested and evaluated. In order to determine the wicking properties of the dressings

<table>
<thead>
<tr>
<th>Product</th>
<th>Manufacturer</th>
<th>Dressing Type</th>
<th>Composition (inner layer/outer layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquacel®</td>
<td>ConvaTec</td>
<td>Nonwoven</td>
<td>100% Hydrofibre®</td>
</tr>
<tr>
<td>Kaltostat®</td>
<td>ConvaTec</td>
<td>Nonwoven</td>
<td>calcium and sodium alginate</td>
</tr>
<tr>
<td>CarboFlex™</td>
<td>ConvaTec</td>
<td>Nonwoven</td>
<td>alginate and Hydrofibre® absorbent/ ACC knit/ alginate and Hydrofibre®/ polyethylene film</td>
</tr>
<tr>
<td>Melolin®</td>
<td>Smith&amp;Nephew</td>
<td>Nonwoven</td>
<td>perforated polyester film/cotton and polyester pad/hydrophobic backing</td>
</tr>
<tr>
<td>CliniSorb®</td>
<td>CliniMed</td>
<td>Nonwoven</td>
<td>polyamide web/ACC woven/polyamide web</td>
</tr>
<tr>
<td>Versiva® XC®</td>
<td>ConvaTec</td>
<td>Foam</td>
<td>Hydrofibre® nonwoven/polyurethane foam/thin adhesive border</td>
</tr>
<tr>
<td>Mepilex® Border</td>
<td>Molnlycke</td>
<td>Foam</td>
<td>silicone gel adhesive/ polyurethane hydrocellular pad/ polyurethane film</td>
</tr>
<tr>
<td>Allevyn Gentle Border</td>
<td>Smith&amp;Nephew</td>
<td>Foam</td>
<td>soft silicone/ polyurethane foam/ polyurethane membrane</td>
</tr>
<tr>
<td>Mepilex®</td>
<td>Molnlycke</td>
<td>Foam</td>
<td>Safetac® soft silicone/polyacrylate nonwoven/ polyurethane foam/polyurethane film</td>
</tr>
<tr>
<td>Mepilex® lite</td>
<td>Molnlycke</td>
<td>Foam</td>
<td>polyethylene foam</td>
</tr>
<tr>
<td>Aqualast® Surgical</td>
<td>ConvaTec</td>
<td>Hydroactive</td>
<td>Hydrofibre® nonwoven pad/CMC stitch bonded with nylon and elastane yarns/polyurethane film</td>
</tr>
<tr>
<td>CombiDERM®</td>
<td>ConvaTec</td>
<td>Hydroactive</td>
<td>nonwoven polypropylene/ sodium polycrylate particles and cellulose pad/ hydrocolloid adhesive/ polyurethane film</td>
</tr>
<tr>
<td>Biatain®</td>
<td>Coloplast</td>
<td>Hydroactive</td>
<td>polyurethane foam/ polyurethane film</td>
</tr>
</tbody>
</table>

2.2. Methods

Selected wound dressing specimens were individually tested and analysed to determine a comprehensive understanding of their fluid handling properties, dehydration rate, dispersion characteristics, vertical wicking, air permeability, swelling characteristic and pH. Prior to all the testing, the dressing specimens were conditioned for 48 hours in 65% relative humidity and 20°C atmosphere [12]. As a preliminary test fluid, solution A was prepared using sodium chloride, calcium chloride dihydrate and de-ionised water. Additionally, Eosine B (red dye, 0.25g/L) was used for vertical wicking test solution.

Solution A was prepared using sodium chloride, calcium chloride dihydrate and de-ionised water. Additionally, Eosine B (red dye, 0.25g/L) was used for vertical wicking test solution.

2.2.2. Absorbency of Wound Dressing

The absorbency of wound dressings was determined by warming to 37±1°C and 40 times the mass equivalent of the specimen was dispensed slowly and gently onto the specimens in the Petri dishes. The Petri dishes were then placed in an incubator for 30 minutes at 37±1°C (body temperature). After 30 minutes of conditioning the dishes were removed from the incubator and suspended by one corner by using tweezers to allow excessive solution to drip off for 30 seconds and reweighed for wet mass.

The calculation of results;

\[
\text{Mass loss upon drying (\%) = } \frac{(B-A) \times 100}{B}
\]

Where; B is the mass of specimens before testing and A is the mass of specimens after testing

2.2.3. Dehydration Rate of Dressing

The dehydration behaviour was determined by measuring the difference between the mass of wet and dry specimens. The specimens were dried in an incubator for 24 hours at 37±1°C. The mass of dry specimens was determined before submerging them in an excess volume of solution A at 37±1°C for 30 minutes. The specimens were taken out from fluid and suspended for a corner by using tweezers for 30 seconds for free drainage. After draining they were re-weighed and put into Petri dishes and kept in an incubator for 24 hours at 37±1°C [16].

The calculation of results;

\[
\text{Dehydration rate (g/min) = } \frac{W-D}{T}
\]

Where; W is the wet mass of specimens, D is the dry mass of specimens, T the test period in minutes

2.2.4. Rate of Absorption

In order to evaluate the rate of absorption, drops of solution A were dropped onto the specimen using an eye dropper on the wound contact layer surface of each dressing and were allowed to fully absorb and the time of absorption was recorded in seconds. 20 drops were dropped onto each dressing and the mean times were calculated [17].

2.2.5. Vertical Wicking

The vertical wicking is one of the important properties for fibrous dressings. This test can be applied only for the fibrous dressings due to the nature of test procedure. The
test specimens were prepared to 15mm width and 100mm length. Eosin B was added into the solution A. The specimens were slowly immersed into the solution vertically up to 10mm length and left for 60 seconds. Vertical wicking of dressings was determined in mm [16,18].

2.2.6. Dispersion Characteristic of Dressing
Dispersions characteristics of the dressings were determined in accordance with BS EN 13726-2:2001, section 3.6. [19]. For this testing, 5cm x5cm dressing specimens were prepared and placed into a 250ml conical flask into which 50 ± 1ml solution A was added. The flask was slowly and gently swirled for 60 seconds. Following which, the specimens were removed and the dispersion was determined visually. The results were expressed as to whether there was dispersion or not in accordance with the standard [20].

2.2.7. Evaluation of Swelling Characteristics
The swelling of fibrous dressings was carried out using Labophot-2 optical microscope at a magnification of 200×. The image Proplus software was used to obtain images of the fibres and the diameters were determined. Solution A was introduced into the fibres without removing fibres from the microscope and was allowed to swell. The image of the swollen fibre was captured and the diameters compared for both dried and wet fibres [21].

2.2.8. Dressing pH Determination
The specimens were suspended into de-ionised water at a ratio of 1:100 (w/v) and were kept at room temperature for 24 hours. The pH was measured by using Consort C831 pH meter. Two measurements were carried out; first after 3 hours; and second after 24 hours. pH meter was calibrated to pH 7 [16,22].

2.2.9. Air Permeability
Air permeability was tested by using the Shirley air permeability tester and it was only applied to fibrous dressings (ASTM D737-96) [23]. Three specimens were evaluated for each type of dressing. The specimens were cut as a circle with 6 cm diameter with a test area of 508mm². Air was admitted into the compartment at one side of the dressing and sucked using a vacuum at the other side of the compartment.

3. Results and Discussion

3.1. Dressing Mass, Thickness and Number of Layers
The mass, thickness and the number of layers of the specimens are given in Table 2. These results show that the masses per unit area of foam and the hydroactive dressings were significantly higher when compared to the nonwoven dressings. The thicknesses of foam and hydroactive dressings were also higher when compared with the nonwoven dressings. These dressings are used in different physical forms such as film, foam, and nonwoven depending on the wound type. The nonwoven structures are mostly used as a single layer or padding (absorbent) layer for multi-layer dressings. For high exuding wounds there are two main types of fibrous dressings currently available and these are carboxymethyl cellulose (CMC) and alginate based dressings. The thinnest to be tested as seen in Tables 2 and 3, are Aquacel® and Kaltostat®. Even though these dressings are single layer, they have the highest fluid absorbency in comparison to the other tested dressings. The multi-layer dressings do show some superior advantages; the main advantage is the possibility of using different components within the dressing to encourage maximum healing and provide protection from external influences. The main disadvantages of multi-layer dressings are their higher cost in comparison to the single layer products; greater bulkiness and the time consuming production processes.

Table 2. Dressing mass, thickness and number of layers

<table>
<thead>
<tr>
<th>Dressing</th>
<th>Dressing Mass (g m⁻²)</th>
<th>Thickness (mm)</th>
<th>Number of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquacel®</td>
<td>108±1.2</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>Kaltostat®</td>
<td>148±4.2</td>
<td>2.0</td>
<td>1</td>
</tr>
<tr>
<td>CarboFlex®</td>
<td>447±5.9</td>
<td>3.9</td>
<td>5</td>
</tr>
<tr>
<td>Melolin®</td>
<td>269±3.3</td>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>CliniSorb®</td>
<td>260±2.0</td>
<td>1.2</td>
<td>3</td>
</tr>
<tr>
<td>Versiva® XC™</td>
<td>1040±12.2</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>Mepilex® Border</td>
<td>828±7.2</td>
<td>4.2</td>
<td>3</td>
</tr>
<tr>
<td>Allevyn Gentle Border</td>
<td>723±3.3</td>
<td>4.2</td>
<td>3</td>
</tr>
<tr>
<td>Mepilex®</td>
<td>696±1.1</td>
<td>5.9</td>
<td>1</td>
</tr>
<tr>
<td>Mepilex® lite</td>
<td>384±0.9</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>Aquacel® Surgical</td>
<td>1128±3.5</td>
<td>4.2</td>
<td>2</td>
</tr>
<tr>
<td>CombiDERM®</td>
<td>633±2.1</td>
<td>1.8</td>
<td>3</td>
</tr>
<tr>
<td>Biatain®</td>
<td>988±2.2</td>
<td>3.4</td>
<td>2</td>
</tr>
</tbody>
</table>

3.2. Absorbency of Wound Dressing
A number of factors can affect the fluid absorption of the dressings [15,20]. The absorption results of dressings are given in Table 3 and Figure 1. It was observed that all the dressing specimens which were examined during this study absorbed at least 4 times their dry mass per unit area of solution A. Aquacel®’s absorption of solution A was considerably higher than most of the other dressings that were studied. Only Kaltostat® and Melolin® dressings had closer values to that of Aquacel®. Aquacel® was second thinnest product after CliniSorb®, yet it was the most absorptive product and reached a peak uptake of 19g/g. However, mass loss of Aquacel® (18%) was higher than the other products. Melolin®, Allevyn Gentle Border, Mepilex®, Mepilex® lite, Aquacel® Surgical and Biatain had no mass loss after complete drying. In general, nonwoven dressings absorbed more fluid than foam and hydroactive dressings. Mass losses of nonwoven dressings were also higher than foam and hydroactive dressings.

It will be observed that the mass and thickness of the dressing did not directly affect its absorption behaviour. Another important finding in this test is that, when the solution was applied to the dressings, sandwiched foam dressing layers separated from each other, the separation fully occurred in Mepilex® Border. This type of separation could affect wound healing process due to the interaction between different layers. There are two scenarios that could explain the effect of this separation on wound healing. In the first scenario, the separation could have negative impact on the wound healing process as there is a lack of exudate transfer between the layers due to the discontinuity of the dressing resulting from their
separation. The second scenario may have a positive influence on the healing process as all layers can continue to perform their main function individually and allow the wound to ‘breathe, thus enhancing the healing process. This aspect requires in-depth, in vivo study, in order to establish the true impact of the separation of dressing layers on the wound healing process.

One-tailed Student’s t-tests were then performed to determine if the fluid handling values of each dressing differed from Aquacel®. The t-values indicate that the difference between the absorbency value of Aquacel® and each wound dressing tested was mostly significant at \( p < 0.05 \). The mean t-value of the Aquacel® against each wound dressing tested is 0.007.

3.3. Dehydration Rate of Dressings

The dehydration properties of the dressings are shown in Figure 2. The dehydration rates varied to some extent for most of the specimens. The dehydration rate has inverse dependency to the thickness of wound dressings, in a manner which decreasing the thickness of the wound dressing causes a decrease in the fraction of water released from it at a specific time [33]. Mepilex® Border had the highest dehydration rate (0.08 g/min) followed by Biatain (0.055g/min). These values are considerably higher than those obtained for the other dressings investigated in this study. The dehydration rate of nonwoven dressings ranged from 0.025g/min to 0.08g/min. It was found that foam and hydroactive dressings had higher dehydration rates in most of the specimens. This can cause maceration.

The rate of absorption was determined for all the specimens and the results for non-fibrous dressings are given in Table 4. The specimens which had fibrous contact layer absorbed the solution A immediately (a sudden intake) which is one of the desired properties for highly exuding wounds. Only CliniSorb® absorbed the drops over 2-4 seconds due to its polyamide layer. It was found that Mepilex® had the slowest solution uptake properties. The nonwoven dressings were closely followed by Biatain with an average rate of absorption of 4 seconds. The results of the study show that all the foam dressings exhibited very poor rate of absorption behaviour due to their closed pore structure. This is an expected outcome since these dressings are used for low exuding wounds. Foam dressings mainly are designed to be in place for periods longer than 24 hours. One of their important properties is to prevent ‘strike-through’ of the wound exudate. This ‘strike-through’ frequently occurs with traditional dressings and provides a pathway for infection [24].

3.5. Vertical Wicking

The vertical wicking was determined for only seven of the wound dressings due to the specimen’s size. CombiDERM® had fibrous contact layer but the size of the absorbent layer was not suitable for this test method. The vertical wicking height of Kaltostat® and Melolin* dressings were found to be 35mm and this was the highest value for the vertical wicking test. CarboFlex™ also showed a high wicking height of 28mm. Hydrofibre®-based dressings Aquacel®, Aquacel® Surgical, and Versiva® XC® had similar vertical wicking values of 13, 15 and 19mm respectively. CliniSorb® had the lowest vertical wicking value of 5mm due to its fibre (polyamide) and fabric structure (woven).

The results show that there is a direct negative relationship between the absorption and vertical wicking characteristics of all the dressings. All Hydrofibre® containing dressings showed higher absorbency properties; however, their vertical wicking properties were found to

### Table 3. Fluid handling properties of dressings

<table>
<thead>
<tr>
<th>Dressing</th>
<th>Fluid Handling (g per g)</th>
<th>Mass loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquacel®</td>
<td>19.07±2.1</td>
<td>18</td>
</tr>
<tr>
<td>Kaltostat®</td>
<td>18.44±1.3</td>
<td>14</td>
</tr>
<tr>
<td>CarboFlex®</td>
<td>11.11±0.5</td>
<td>11</td>
</tr>
<tr>
<td>Melolin®</td>
<td>13.56±0.6</td>
<td>0</td>
</tr>
<tr>
<td>CliniSorb®</td>
<td>3.54±0.2</td>
<td>6</td>
</tr>
<tr>
<td>Versiva® XC®</td>
<td>4.16±0.4</td>
<td>5</td>
</tr>
<tr>
<td>Mepilex® Border</td>
<td>7.71±1.0</td>
<td>20</td>
</tr>
</tbody>
</table>

### Table 4. Rate of absorption of dressings

<table>
<thead>
<tr>
<th>Dressings</th>
<th>Mepilex® Border</th>
<th>Allevyn Gentle Border</th>
<th>Mepilex®</th>
<th>Mepilex® lite</th>
<th>Biatain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of absorption in second</td>
<td>16</td>
<td>32</td>
<td>More than 10 minutes</td>
<td>206</td>
<td>4</td>
</tr>
</tbody>
</table>

The specimens which had fibrous contact layer absorbed the solution A immediately (a sudden intake) which is one of the desired properties for highly exuding wounds. Only CliniSorb® absorbed the drops over 2-4 seconds due to its polyamide layer. It was found that Mepilex® had the slowest solution uptake properties. The nonwoven dressings were closely followed by Biatain with an average rate of absorption of 4 seconds. The results of the study show that all the foam dressings exhibited very poor rate of absorption behaviour due to their closed pore structure. This is an expected outcome since these dressings are used for low exuding wounds. Foam dressings mainly are designed to be in place for periods longer than 24 hours. One of their important properties is to prevent ‘strike-through’ of the wound exudate. This ‘strike-through’ frequently occurs with traditional dressings and provides a pathway for infection [24].

3.4. Rate of Absorption

### Table 4. Rate of absorption of dressings

<table>
<thead>
<tr>
<th>Dressings</th>
<th>Mepilex® Border</th>
<th>Allevyn Gentle Border</th>
<th>Mepilex®</th>
<th>Mepilex® lite</th>
<th>Biatain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of absorption in second</td>
<td>16</td>
<td>32</td>
<td>More than 10 minutes</td>
<td>206</td>
<td>4</td>
</tr>
</tbody>
</table>
be inferior. This is due to the fact that Hydrofibre® can absorb a considerable amount of fluid resulting in a large increase in the fibre diameter during the testing period of one minute. This prevents the fluid to travel along the length of the fibre thus giving rise to a lower vertical wicking behaviour.

3.6. Dispersion Characteristic of Dressings

The dispersion test method determines how the physical characteristic of the dressings change when they interact with fluid. The dispersion characteristics of the dressings must be known due to the removal of the dressings from the wounds. The relationship between dispersion and the wound healing process have been discussed elsewhere [25]. Pain free removal is one of the most desired characteristics for wound dressings. In this case, dressings could be able to maintain enough integrity for the painless removal. The dispersions were observed visually from all the fibrous dressings except CliniSorb® because of its structural and material properties. It was observed that Aquacel®, Kaltostat®, CarboFlex™, Melolin*, and CombiDERM® dressings were completely dispersed in the solution A when they were immersed in it.

3.7. Evaluation of Swelling Characteristics

The swelling characteristics of the fibrous dressings were determined by using a microscope with a 40× magnification. The test was performed on only eight fibrous dressings due to the nature of test method. The fibre images were captured in the dry and swollen states. The typical Hydrofibre® fibre images are shown in Figure 3 to demonstrate the difference between the dry and swollen fibres (Table 5). The swelling ratios of the fibres were determined by measuring the diameter of the dry and swollen fibres. The swelling ratio (Q) of the dressings was calculated by using following equation:

\[ Q = \frac{(D_s - D_o)}{D_o} \]

where \( D_s \) is the swollen state and \( D_o \) is the dry state (original) diameters in µm.

<table>
<thead>
<tr>
<th>Dressing type</th>
<th>Dry diameter (µm)</th>
<th>Swollen diameter (µm)</th>
<th>Swelling ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquacel®</td>
<td>10.9</td>
<td>42.3</td>
<td>2.88</td>
</tr>
<tr>
<td>Kaltostat®</td>
<td>12.4</td>
<td>19.1</td>
<td>0.54</td>
</tr>
<tr>
<td>CarboFlex™</td>
<td>12.7</td>
<td>35.3</td>
<td>1.78</td>
</tr>
<tr>
<td>Melolin*</td>
<td>15.2</td>
<td>17.5</td>
<td>0.15</td>
</tr>
<tr>
<td>CliniSorb®</td>
<td>8.5</td>
<td>9.3</td>
<td>0.09</td>
</tr>
<tr>
<td>Versiva® XC®</td>
<td>10.5</td>
<td>40.1</td>
<td>2.82</td>
</tr>
<tr>
<td>Aquacel® Surgical</td>
<td>10.6</td>
<td>39.5</td>
<td>2.73</td>
</tr>
<tr>
<td>CombiDERM®</td>
<td>14.2</td>
<td>18.6</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The fibre swelling results clearly demonstrate that as expected the Hydrofibre® containing dressings Aquacel®, Aquacel® Surgical and Versiva® XC® showed very similar swelling behaviour and their swelling ratios were found to be higher than the other fibrous dressings. They swelled to around three times their original diameters when they were treated with solution A. CarboFlex™ absorbent fibrous contact layer swelled around two times and the second layer consisting of ACC fibres did not swell at all. Kaltostat® swelled around 0.54 times its original diameter which was too low as compared to its absorption properties. The swelling of Melolin* was determined to be around 0.15 times which was also too low as compared to its absorption values. CombiDERM® swelled 0.31 times and CliniSorb® contact layer swelled 0.09 times.

3.8. Dressing pH Determination

It can be observed from Figure 4 that there are noteworthy differences between the pH values tested after 3 and 24 hour periods. In all the dressings tested, the pH values increased when tested after an immersion period of 24 hours. The pH values of foam and hydroactive dressings were found to be slightly higher than the nonwoven dressings. After 3 hours, pH values ranged from 5.25 to 6.35, but after 24 hours, the pH values ranged from 5.95 to 7.90. It can be hypothesised that the acidification of the dressings decreases, as the application period of the dressings increases. This increase in the pH value can also adversely affect the wound healing process. The pH value within the wound-milieu influences, indirectly and directly, all biochemical reactions taking place in the healing process. If this is the case then it is not advisable to keep these dressings in situ for long periods of time as this will affect the pH balance. Importantly, as the wound progresses towards healing, the pH value moves to neutral and then becomes acidic [28]. In previous studies, the pH environment of chronic wounds has been recorded to be within the range of 7.15-8.9 [28,29]. Some research works have also concluded that the wound pH value is directly related to the tissue type as well as wound exudate and not the grade of wound [30,31].
through the dressing in one second from 100 mm² of the Aquacel®, Aquacel® Surgical and Versiva® XC® had the rate of dehydration between dressings in this study. There are no noteworthy differences in the foam dressings do not absorb quickly as compared to other dressings. There are no noteworthy differences in the rate of dehydration between dressings in this study. Aquacel®, Aquacel® Surgical and Versiva® XC® had lower vertical wicking than Kaltostat® and Melolin®. The pH values of nonwoven dressings are lower than the foam and hydroactive dressings, which are mainly due to their light weight, lower thickness and density, and porous structures (Table 6). CarboFlex™ Melolin® and CliniSorb® showed similar air permeability values. The air permeability is one of the important parameters of wound dressings, which prevents maceration and gives a better comfort to the patients. In a recent in vivo study on wound healing and antibacterial performance of electrospun nanofibre membranes, the authors concluded that the porosity and air permeability characteristics have a strong influence on facilitating the wound healing, especially at the early healing stages [32]. Table 6 reveals that the nonwoven dressings have superior air permeability characteristics when compared to foam and hydroactive dressings, which are mainly due to their relatively open structures.

### 3.9. Air Permeability

The air permeability is a quantitative measurement of how well a material allows the passage of air through it. It can be defined the volume of air in mm³ which is passed through the dressing in one second from 100mm² of the fabric at a pressure of 10 mm head of water. Aquacel® and Kaltostat® had the highest air permeability due to their light weight, lower thickness and density, and porous structures (Table 6). CarboFlex™ Melolin® and CliniSorb® showed similar air permeability values. The air permeability is one of the important parameters of wound dressings, which prevents maceration and gives a better comfort to the patients. In a recent in vivo study on wound healing and antibacterial performance of electrospun nanofibre membranes, the authors concluded that the porosity and air permeability characteristics have a strong influence on facilitating the wound healing, especially at the early healing stages [32]. Table 6 reveals that the nonwoven dressings have superior air permeability characteristics when compared to foam and hydroactive dressings, which are mainly due to their relatively open structures.

<table>
<thead>
<tr>
<th>Dressings</th>
<th>Air permeability (cm³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquacel®</td>
<td>1380</td>
</tr>
<tr>
<td>Kaltostat®</td>
<td>1104</td>
</tr>
<tr>
<td>CarboFlex™</td>
<td>280</td>
</tr>
<tr>
<td>Melolin*</td>
<td>288</td>
</tr>
<tr>
<td>CliniSorb®</td>
<td>345</td>
</tr>
</tbody>
</table>

### 4. Conclusions

In this section, in vitro testing and evaluation of the thirteen wound dressings demonstrated that Aquacel® is the most absorptive wound dressing, although it was lighter than the other dressings tested. It was followed by Kaltostat® and CliniSorb in terms of dressing mass. It is clearly demonstrated that the nonwoven dressings have better absorbency characteristics than foam and hydroactive dressings, due to their fibre properties and porous structure. If the absorbency of the dressing aids wound healing, then nonwoven dressings should be more effective than the foam and hydroactive dressings. There was a considerable difference in the rate of absorption between the nonwoven dressings, foam dressings and hydroactive dressings. The nonwoven dressings absorbed the solution immediately, which is a preferred characteristic for bleeding wounds. It is also observed that the foam dressings do not absorb quickly as compared to other dressings. There are no noteworthy differences in the rate of dehydration between dressings in this study. Aquacel®, Aquacel® Surgical and Versiva® XC® had lower vertical wicking than Kaltostat® and Melolin®. The pH values of nonwoven dressings are lower than the foam and hydroactive dressings for 3 and 24 hours immersion in distilled water. It can be suggested that the nonwoven dressings are more effective in terms of healing time because they facilitate in achieving an acidic wound surface. This section provides an in-depth understanding of relationship between the wound dressing structures and their properties. The inferences drawn from this section are crucial in order to design and develop more effective and novel modern wound dressings.

### Acknowledgements

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