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Real-time monitoring of moisture levels in wound dressings *in vitro*: An experimental study

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Abstract Retaining an appropriate level of moisture at the interface between a healing wound and an applied dressing is considered to be critical for effective wound healing. Failure to control exudate at this interface can result in maceration or drying out of the wound surface. The ability to control moisture balance at the wound interface is therefore a key aspect of wound dressing performance. To date it has not been possible to monitor in any effective manner the distribution of moisture within dressings or how this varies with time.

A new measurement system is presented based on sensors placed at the wound/dressing interface which are capable of monitoring moisture levels in real time. The system comprises a model wound bed and sensor array complete with fluid injection path to mimic exudate flow. Eight monitoring points, situated beneath the test dressing, allow the moisture profile across the complete dressing to be measured both during and after fluid injection.

The system has been used to evaluate the performance of four foam dressings, a composite hydrofibre dressing and a film dressing. Stark contrasts in the performance of the wound contact layer were found between the different wound dressing types. The composite hydrofibre dressing retained moisture at the wound interface throughout the experiments while areas of the foam dressing quickly became dry, even during constant injection of fluid. The abundance of sensors allowed a moisture map of the surface of the wound dressing to be constructed, illustrating that the moisture profile was not uniform across several of the dressings tested during absorption and evaporation of liquid. These results raise questions as to how the dressings behave on a wound *in vivo* and indicate the need for a similar clinical monitoring system for tracking wound moisture levels.

Introduction

Moisture balance

The presence of moisture avoids the delay in healing response which occurs when wounds are allowed to dry out.[1] Excessive fluid retention at the wound surface, however,

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can result in poor healing and maceration of the surrounding tissue.[2] This means that a delicate fluid balance must be achieved at the wound/dressing interface to provide sufficient moisture for cellular activity without adversely affecting healing.[3]

The evaluation of moisture under wound dressings and the volumes required for moist wound healing tend to be qualitative rather than quantitative. A proven method of monitoring fluid retention at the wound surface/dressing interface is therefore required.

Wound dressing tests

Clinical trials are the ideal environment for the validation of wound dressing performance,[4] however, they can be costly and time consuming. As a result, wound dressings are subjected to a variety of preclinical studies including *in vivo* and *in vitro* studies with a range of biological cell types and substitute fluids and tissues.[5–9]

Different hydrocolloid dressings can be compared using a variety of laboratory tests including moisture vapour transfer rate (MVTR), fluid handling properties, gelling characteristics and conformability.[10,11] These tests, however, are not modelled on continually exuding wounds and thus have limitations.

Development of a standard for the characterisation of the wound/dressing interface could provide information to aid in the further development of modern wound dressings.

Bioimpedance

Electrical impedance allows for the detection of ionic (electrically conductive) liquids based on the principle that the higher the impedance, the lower the volume of liquid present. Since wound exudate is essentially an ionic liquid it is possible to identify its presence and quantity by applying an alternating current (AC) of varying frequency, f, in the local environment.

The study of biological impedance has developed links between changes in tissue impedance and physiological effects such as tumour growth, blood flow and skin permeability.[12–14] This has been extended to monitoring the condition of healing wounds such as surgical wounds[15–17] and wounds under wound dressings.[18,19]

Direct current (DC) electrical resistance measurements have been applied to wound dressings *in vitro* to detect fluid strike-through to the external surface of the dressing,[20] although this does not provide a quantitative measure of wound dressing hydration.

The aim of our study was therefore:

- To design a suitable wound bed model that could be utilised to mimic exudate flow into a dressing
- To investigate the use of new proximity moisture sensors based on paired silver/silver chloride (Ag/AgCl) electrodes for the detection of moisture in wound dressings
- To use the wound bed and sensor system to test the moisture retention capacity of a range of current advanced wound dressings.

Materials and methods

The moisture handling characteristics of wound dressings were tested in two stages:

1. Hydrated wound dressings were monitored for rate of dehydration through simultaneous measurements of the mass of the liquid in the dressing and the electrical impedance at the wound/dressing interface.
2. A model wound bed was devised to provide a wound-contact surface for dressings. Impedance sensors embedded in the system allowed the moisture profile across the surface to be determined with respect to time.

Effects of dehydration on impedance and mass of liquid

The system used to determine the relationship between electrical impedance and mass of liquid in the dressings comprised a Perspex chamber, an electronic balance, a 5 V/3 A heat mat, and an analogue hygrometer (Fig. 1). Wound dressings were monitored by electrical impedance as dehydration occurred. The dressings were weighed at regular intervals to record the relationship between change in impedance and loss of moisture. The dressings evaluated are illustrated in Table 1.

Figure 1 Manual weighing system, within the environmental control chamber, showing electronic balance, heat mat, test dish and dressing sample.

Table 1 Description of dressings tested

Trade name	Dressing type
Versiva (ConvaTec)	Hydrocolloid/Hydrofibre®
Allevyn™ (Smith & Nephew)	Polyurethane foam
Biatain™ (Coloplast)	Polyurethane foam
Tielle™ (Johnson & Johnson)	Polyurethane foam
Tielle™ Plus (Johnson & Johnson)	Polyurethane foam
OpSite™ (Smith & Nephew)	Polyurethane film

All dressings indicated for moderately exuding wounds with the exception of Tielle™ Plus and OpSite which are indicated for heavy and lightly exuding wounds respectively.

Mass measurements (to monitor liquid loss) were performed manually with the digital balance (Sartorius, Germany) at intervals of 2 h. The dressing was removed from the heat mat to be weighed, which disturbed the test environment for about 60 s during every measurement.

Impedance was determined with Ag/AgCl electrodes insulated with silicon elastomer (Syndev 2, BDH, UK) that were inserted into whole wound dressings. Measurements were performed using a 1260 impedance analyser (Solartron, UK).

Electrodes were inserted through two small incisions, 2 cm apart, made in the backing of the dressing (or at the edge of a perforation for perforated dressings) and the dressing was applied to the petri dish. As the incisions allowed pathways for moisture vapour transfer, the electrodes were sealed in place using a small amount of beeswax. Connecting wires were added and fixed in place before the ensemble was weighed.

British Pharmacopoeia Solution A (142 mM NaCl, 2.5 mM $CaCl \cdot 2H_2O$ in distilled water)[21] was injected into the dressings at four individual sites around the centre of the dressing. The volume injected was dependent on the wound dressing dimensions (The maximum loading was 10 ml for a 10 cm × 10 cm dressing). The injection points were sealed with beeswax and the dish and its contents were again weighed to provide the starting mass.

The dressing was placed directly over the heat mat and connected to the impedance analyser. The chamber was sealed to maintain constant humidity and temperature.

Impedance data were recorded constantly for periods of 2 h at frequency 1 kHz and voltage amplitude 200 mV. The 1 kHz frequency yields impedance pertinent to ionic conductivity in the solution. Every 2 h the dressing was disconnected, the ensemble weighed, reconnected and the impedance measurement restarted. Impedance data were constantly recorded overnight up to a period of 16 h. When the test period was complete the ensemble was weighed to provide a final mass reading for the sample.

Moisture mapping of the wound/dressing interface

Moisture maps of the wound dressing contact surface were obtained using a custom-made test rig containing eight equally spaced Ag/AgCl electrode pairs capable of measuring local changes in liquid impedance (referred to as sensors) and a simulated wound bed of dimensions 6 cm × 6 cm (Fig. 2).

The model wound bed

The surface layer of the wound bed is fabricated from polytetrafluoroethylene (PTFE), which is thermally conducting, electrically insulating and resistant to solvents which may be required to remove wound dressing adhesive residue. The surface layer is heated by an underlying heat mat.

The wound is simulated by a curving track (4 mm depth and width) cut into the surface of the PTFE layer, capable of directing Solution A around the surface between the sensors. A cellulose dialysis membrane (Sigma, UK), was placed over the track and sensors to allow uniform spread of liquid over the surface of the wound model and prevent expansion of the dressings into the track. The membrane was cut to 7 cm × 7 cm and was soaked in test solution for 24 h prior to use.

The sensor array embedded in the wound bed

The hydration of the membrane is monitored by means of impedance measurements, collected from the eight sensors (Fig. 2). The sensors were positioned in the wound bed with a separation of 18 mm between the centres of each

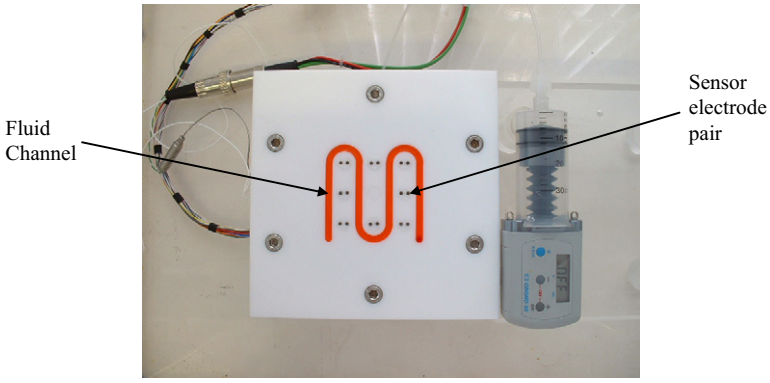

Figure 2 Model wound bed, a channel cut into the surface of the PTFE contact plate is filled with red liquid in this image to illustrate the liquid flow path selected to emulate the arrival of wound exudate at dressing surface. The eight sensor electrode pairs for localised impedance measurement are embedded in the model wound bed, flush with the surface, as shown above.

measurement location. The surface temperature was maintained at 33 °C using a feedback loop between a thermocouple embedded in the wound bed, a temperature controller and the heat mat.

Impedance measurements from the sensor array
Impedance measurements were obtained from eight channels using a 1281 Multiplexer (Solartron, UK) in addition to the 1260 impedance analyser. Each sensor was scanned hourly during the test period and the data recorded at 1 kHz were selected to determine the impedance of the sample.

Wound dressings testing on wound model system
Dressings were applied covering the dialysis membrane, with the centre of the dressing placed over the track and sensors. The test rig and a syringe pump (Crane Srl Elettronica Medicale, Italy) were placed in the environmental chamber where relative humidity was maintained at 50 ± 2% throughout each experiment. Solution A was pumped through the test rig at a rate of 0.5 ml/cm^2 per 24 h, which is equivalent to a moderately exuding wound.[22] The pump was stopped after 8 h and impedance measurements continued for a further 16 h. This procedure was carried out for five replicates of each dressing, with the exception of OpSite™, which was only tested once as a non-absorbent adhesive dressing reference.

Results

Effects of dehydration on impedance and mass of liquid

In the first experiment, performed to determine how mass and impedance changed within a dressing using a single sensor pair, the dehydration of the wound dressings was observed over a period of 48 h with only Biatain™ retaining fluid until the end of the test. A plot illustrating the relationship between the impedance measured by the electrodes and the percentage of liquid lost is shown in Fig. 3. Impedance data obtained when the fluid loss was 100% were omitted from this graph, since these produced data points of values greater 200 kΩ, skewing the graph scale and reducing the clarity of the lower impedance data when dressings were hydrated. As the mass of liquid in the dressing falls below 50% of the initial fluid load the impedance measured by the electrodes begins to increase. This increase in impedance can be attributed to the low levels of fluid in the wound dressing.

Moisture mapping of the wound/dressing interface

In the second experiment the impedance measured at the surface of the wound dressing, through individual measurements across all eight sensors on the wound bed, indicated whether or not the wound dressing was acting to retain fluid at the wound bed surface. A selection of readings from the eight sensors when monitoring different types of hydrated dressings is illustrated in Table 2. It was generally observed that the impedance was low, less than 15 kΩ, over the first 8 h of the experiment. These low values of impedance suggest that the wound/dressing interface is moist while fluid is being injected into the apparatus.

As the test progressed, the impedance measured by the sensors began to increase. This generally occurred once the fluid injection ceased, however, high impedance was detected in some samples of Tielle™ before fluid injection had been completed. Once the dry out period was entered (8—24 h) the impedance reached values greater than 200 kΩ. This coincides with dehydration of the dressing and means that the dressing contact surface has become dry.

Discussion

It has been demonstrated that electrical impedance measured within a dressing can be indicative of the level of liquid that is present. This can usefully be employed to determine a range of impedance values that correspond to different levels of moisture in a dressing. The aim in the

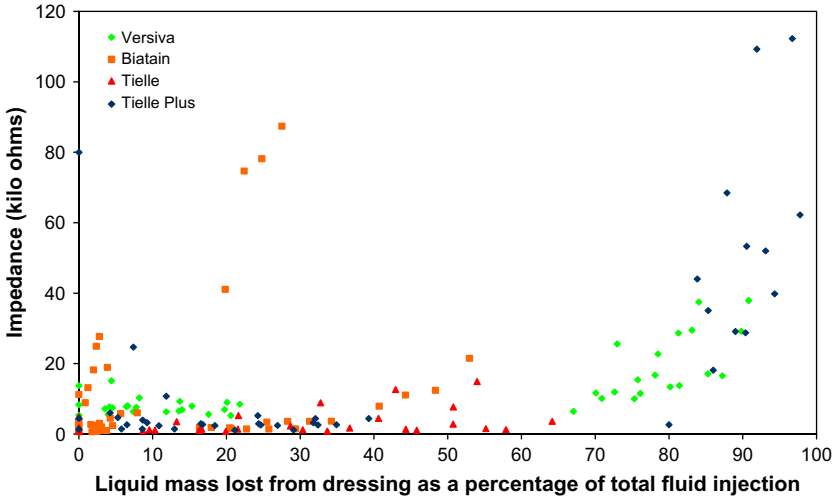

Figure 3 Relationship between the percentage of liquid lost from the dressing and the impedance measured between two silver wire electrodes embedded in the dressing. The data represents a total of twenty samples obtained from four individual dressing types: Versiva®, Biatain™, Tielle™ and Tielle™ Plus.

Table 2 Examples of impedance data from single sensors when a variety of dressings were tested

Time (h)	OpSite	Versiva	Allevyn	Biatain	Tielle
0	2.19	3.68	5.63	3.30	3.65
1	1.39	3.14	3.49	2.28	2.02
4	1.18	3.39	3.15	2.39	1.79
8	1.02	3.32	3.12	2.21	3.00
12	1.13	4.56	3.16	3.75	376.11
16	1.17	4.55	3.17	12.29	382.99
20	1.11	5.10	48.78	163.58	368.28
24	1.19	7.04	282.87	463.05	368.77

The impedance values are given in kiloohms.

future is to further develop this approach in order to provide a clinical, diagnostic tool that can non-invasively predict the hydration status of a wound dressing without having to disturb the wound or dressing.

Effects of dehydration on impedance and mass of liquid

As the mass of liquid within the wound dressing decreased there was a corresponding rise in the impedance. To determine the impedance ranges that might correspond to low or high moisture hydration levels an averaging process across the mass—impedance data points, using the results for all dressings and samples, was utilised together with physical observation of the dressings to confirm hydration status. Some outliers, where points clearly corresponded to observed anomalies such as pockets of liquid, were removed from the averaging process. The bands of impedance values corresponding to wet (saturated) through high moisture, low moisture, very low moisture and dry were constructed by taking the averaged mass—impedance measurements and linking these to observed physical status of the dressings to draw the boundaries between moisture conditions (see Fig. 4). This approach gave an initial scale to relate impedance value with dressing hydration state and this was confirmed by observations made of the dressings at the various stages. The resulting moisture scale for impedance is shown in Table 3. It is from this scale that the colour maps illustrating the topography of the wound contact layer of the dressing can be assembled.

Table 3 Scoring scale relating moisture to impedance indicative of the condition of the wound/dressing interface

Impedance (kΩ)	Condition	Colour
<1.4	Wet	Blue
1.4—15	High moisture	Green
15—50	Low moisture	Yellow
50—200	Very low moisture	Orange
>200	Dry	Red

There may be some question about the justification of averaging across the different dressing types to create this single graph, however, as a first attempt at looking at the limits of such a monitoring system it provides an insight to the extremes that occur. In future detailed studies it would be preferable to create scales for individual dressing types or for clinical wound categories. In this first study of the wound bed model and hydration sensors, the selected moisture—impedance bands provide an effective illustration of how the system might be used to determine the moisture status in a dressing.

Moisture mapping of the wound/dressing interface

The conditions outlined in Table 3 were each assigned a colour to provide a simple means of identifying the level of

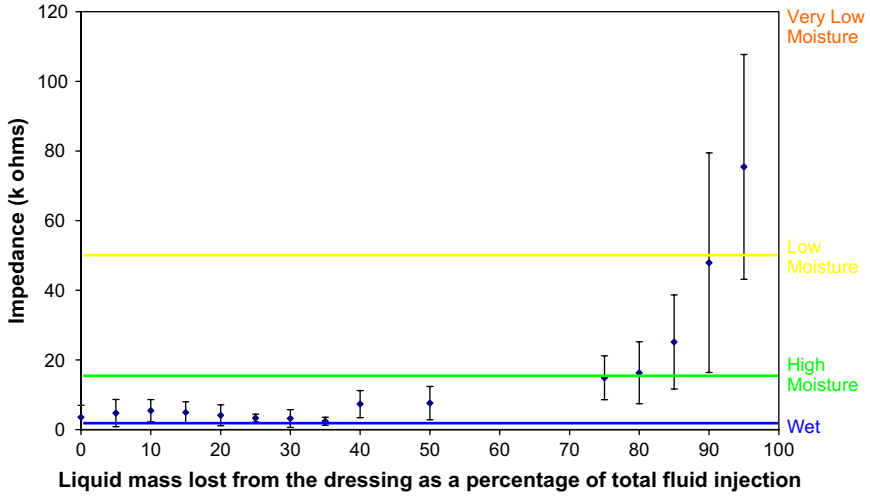

Figure 4 Determination of an initial hydration scale linked to impedance, fluid loss and observed status of dressing material. The horizontal coloured lines demarcate boundaries between different degrees of hydration. The data points show the average impedance obtained against percentage fluid loss across all dressing samples (standard deviation bars are shown also). Data points appearing below the blue line would indicate saturation (liquid environment), below the green line would indicate high levels of moisture and below the yellow line low moisture. Above the yellow line and up until impedance values of 200 kΩ (off-scale) the status is very low moisture, after 200 kΩ the status of the dressing is dry.

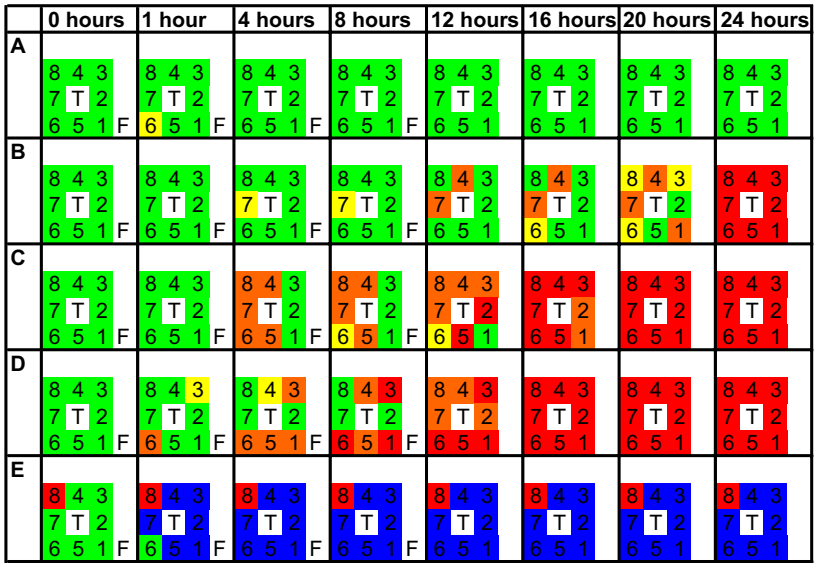

Figure 5 Average maps for each wound dressing tested with Solution A. Dressings are labelled on the left: A, Versiva®; B, Allevyn®; C, Biatain™; D. Tielle™; E. OpSite™. The numbers within the squares indicate the sensors (plugs), T represents the thermocouple and F represents fluid input to the rig. Blue indicates impedance lower than 1.4 kΩ (maceration), green sections indicate impedance in the range 1.4—15 kΩ (moist/optimal), yellow indicates 15—50 kΩ (sub optimal moisture), orange indicates impedance in the range 50—200 kΩ (low moisture/potential cellular dehydration) and red indicates impedance greater than 200 kΩ (potential adhesion to wound bed).

hydration. These colours were then applied to grids representative of the wound bed surface and the position of the sensors. These grids were arranged to provide a simple way of identifying changes in moisture retention at the wound dressing surface over the course of continuous hydration followed by continuous dehydration.

The moisture maps (Fig. 5) allow the greatly varying results between dressing types to be easily identified. In these experiments Versiva® clearly retains moisture at the wound contact surface of the wound dressing for up to 16 h without further hydration. The foam dressings did not retain fluid to the same extent after the fluid injection ceased since, on average, all of the dressings were dry at the wound contact surface at 24 h. OpSite™, on the other hand, retained too great a volume of liquid within the wound model, which is to be expected since the dressing is not designed to absorb fluid but instead relies purely on water vapour transfer.

The results at 24 h could be validated easily by visual inspection of the membrane and wound dressing following removal from the apparatus. Membrane that had been covered with Versiva® tended to be oily and wet to the touch, while membrane that had been in contact with the foam dressings was rigid and dry to the touch. When OpSite™ was removed from the apparatus there was approximately 7 ml of excess liquid in the system, meaning that approximately 3 ml evaporated over 24 h. The WVTR was calculated from this volume and the 36 cm^2 area of the wound bed giving a WVTR of 833 g/m^2 per 24 h, which is in close agreement with the value quoted in the literature, 862 g/m^2 per 24 h.[23]

Although the moisture profile of Versiva® appears fairly constant throughout the experiment each electrode pair within the multielectrode wound model works independently providing hydration information local to each specific pair. This is most evident with foam dressings since there are great variations in the location of surface moisture. These variations occur since the foam dressings have a tendency to expand. This means that there are intermittent areas of intimate contact at the surface which varies the profile.

The wound bed model described is, of course, not a real wound and is therefore limited in terms of realistically modelling a wound. There are also technical areas that could be improved upon to provide an accurate measure of surface moisture. For instance, the results shown for OpSite™ illustrated that the presence of an air bubble over one of the electrode pairs gave a very high reading for impedance, which would indicate no moisture, despite there being 7 ml of fluid under the wound dressing.

Other possible deficiencies of the model can be found in the fluid and method of fluid delivery. The solution used in the experiments presented in this study has a similar ionic concentration to animal serum and is used as an industry standard to replace exudate. However, the exact conductivity of clinical wound exudate has yet to be measured. Fluid was pumped into the model at a constant rate over a period of 8 h, which, it can be argued, is unlike a real wound. This study should be considered as a starting point as sensors have yet to be applied to wounds to determine the moisture located under a wound dressing *in vivo*.

Conclusions

A wound model containing a multi-sensor array for monitoring the wound contact surface of the wound dressings was designed and fabricated. This system was used to illustrate that moisture status of wound dressings can be assessed non-invasively using small electric currents and

the resulting measurements provided insights into the behaviour of various wound dressing types. To further develop the system it will be necessary to test various dressings under differing exudate flow rates and times and also to consider adapting the system to allow the testing of dressings in different, simulated clinical protocols such as in compression bandaging.

The results suggest that the system could be further developed and applied to wound dressings *in vivo* to indicate the condition of a wound under a wound dressing without causing irritation or further damage to a healing wound.

Conflicts of interest
None.

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Ethical approval
Not required.

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References

1. Winter GD. Formation of the scab and the rate of epithelialization of superficial wounds in the skin of the young domestic pig. *Nature* 1962;**193**:293—4.
2. Cutting KF, White RJ. Maceration of the skin and wound bed. 1: Its nature and causes. *J Wound Care* 2002;**11**:275—8.
3. Bishop SM, Walker M, Rogers AA, Chen WYJ. Moisture balance: optimising the wound-dressing interface. *J Wound Care* 2003; **12**:125—8.
4. Campbell KE, Keast D, Woodbury G, Houghton P. Wear time in two hydrocolloid dressings using a novel in vivo model. *Wounds* 2003;**15**:40—8.
5. Cochrane C, Rippon MG, Rogers A, Walmsley R, Knottenbelt D, Bowler P. Application of an in vitro model to evaluate bioadhesion of fibroblasts and epithelial cells to two different dressings. *Biomaterials* 1999;**20**:1237—44.
6. Waring MJ, Parsons S. Physico-chemical characterisation of carboxymethylated spun cellulose fibres. *Biomaterials* 2001; **22**:903—12.
7. Newman GR, Walker M, Hobot JA, Bowler P. Visualisation of bacterial sequestration and bactericidal activity within hydrating Hydrofiber wound dressings. *Biomaterials* 2006;**27**:1129—39.
8. Berscht PC, Nies B, Liebendörfer A, Kreuter J. In vitro evaluation of biocompatibility of different wound dressing materials. *J Mater Med* 1995;**6**:201—5.
9. Choi YS, Lee SB, Hong SR, Lee YM, Song KW, Park MH. Studies on gelatin-based sponges. *J Mater Sci Mater Med* 2001;**12**: 67—73.
10. Thomas S, Loveless P. A comparative study of the properties of six hydrocolloid dressings. *Pharm J* 1991;**247**:672—5.
11. British Pharmacopoeia, *Semipermeable hydrocolloid dressing, British Pharmacopoeia Addendum*. London: HMSO; 1996. p. 1943—4.
12. Zou Y, Guo Z. A review of electrical impedance techniques for breast cancer detection. *Med Eng Phys* 2003;**25**:79—90.
13. Costeloe K, Smyth DP, Murdoch N, Rolfe P, Tizard JPM. A comparison between electrical-impedance and strain-gauge plethysmography for the study of cerebral blood-flow in the newborn. *Pediatr Res* 1984;**18**:290—5.
14. Burnette RR, Bagniefski TM. Influence of constant current iontophoresis on the impedance and passive Na^+ permeability of excised nude mouse skin. *J Pharm Sci* 1988;**77**:492—7.
15. Harrison DH, Mott G. Impedance monitoring for subcutaneous free flap transfers. *Br J Plast Surg* 1989;**42**:318—23.
16. Davies AH, Horrocks M. Non-invasive impedance in graft surveillance. *Ann Chir Gynaecol* 1992;**81**:227—30.
17. Adam L, Tadmor A, Aizinbud E, Schindler H. Electrical impedance monitoring of the wound-healing process. *Med Prog Technol* 1983;**9**:227—32.
18. McAdams ET. Tissue mapping system using impedance. *World Wide Patent Application*; 2004 [WO2004049937].
19. Petrofsky JS. Wound healing with feedback control. *World Wide Patent Application*; 2004 [WO2004080534].
20. Thomas S, Fram P. The development of a novel technique for predicting the exudate handling properties of modern wound dressings. *World Wide Wounds*; 2001.
21. British Pharmacopoeia, *Sodium chloride and calcium chloride solution. British Pharmacopoeia Addendum*. London: HMSO; 1995.
22. Thomas S, Fear M, Humphreys J, Disley L, Waring MJ. The effect of dressings on the production of exudate from venous leg ulcers. *Wounds* 1996;**8**:145—50.
23. Thomas S. *Wound management and dressings*. London: Pharmaceutical Press; 1990.