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Review Article

Adapting resistive sensors for monitoring moisture in smart wound dressings

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Abstract
Moisture plays a critical role in the wound healing process and, given the multitude of electrochemical sensors aimed at measuring humidity, it is somewhat surprising that there are few systems dedicated to this particular application. The issues relating to wound moisture and the practical challenges facing the adaptation of generic resistive moisture sensors to this area are considered along with the potential impact such systems could have on nursing practice.

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Introduction

Most slow healing (chronic) wounds are managed in the community by district nursing/primary care practice nurses and recent estimates by Guest et al. (2015) indicate that of 2.2 million wounds treated annually by the UK NHS, 1.45 million are managed by community nurses [1]. Maybin et al. [2] also highlight the changing patterns in community nursing, where increased numbers of patients, and the complexity of the care required, places considerable stress on existing healthcare systems. Given the likely increases in demand, it has been suggested that expenditure on healthcare services will fail to keep pace, and more fundamental changes will be required in the manner in which wound care is delivered [2,3]. The changing community care landscape offers considerable opportunities for the development of point-of-care devices and connected health systems that offer detailed telemetry of the patient's condition. The ideal embodiment of such a system is summarised in Figure 1 and it is possible to envisage that the provision of sensors that can acquire detailed information on a spectrum of wound biomarkers could, in principle, dramatically aid clinical decision making and improve patient outcomes.

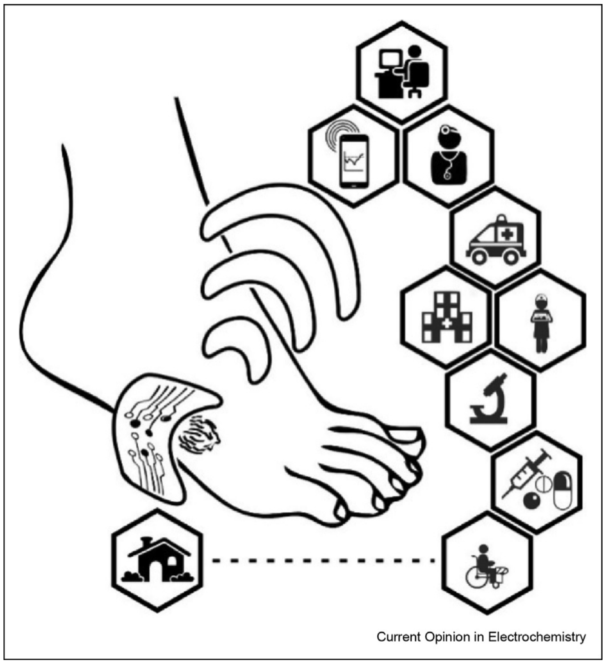
Understanding the significance of the various biochemical players, the nuances associated with changes in their concentrations and the corresponding impact on cellular regeneration however are, much like the technologies required to monitor them, at very early stages of development. As such, few systems have been able to reach commercial maturity and, in most cases, the development cycle tends to become entangled at the proof-of-concept stage, and there are a number of reviews on emerging and future developments within the field [4–6]. Yet, it could be argued that the sensing technologies required to make substantive differences to wound management in the present, already exist. Monitoring simple parameters such as moisture associated with the wound fluid have long been recognised as key parameters in the day to day management of complex wounds.

The aim of this perspective has been to provide some critical insights into the translation of resistive sensor technologies for monitoring moisture levels (particularly relative humidity, RH) within conventional wound dressings. Rather than providing an exhaustive examination of RH sensors, the focus is on highlighting some recent developments and their applicability to the particular requirements of wound diagnostics and potential value to decentralised community wound management.

The significance of moisture in wound care

The provision of a moist wound environment has been a key tenet of wound care since the seminal papers of Winter in the 1960s [7–10] and is often regarded as the single most significant advance in wound care in recent

Figure 1



Idealised smart wound dressing enabling telemetry of the wound environment that can aid healing and provide proactive monitoring of complications and infection.

decades. Maintaining an adequate level of hydration within the wound bed has been shown to be critical to facilitating the operation of the biochemical reactions that are responsible for triggering the granulation and re-epithelialisation processes that expediate wound healing. In contrast, the presence of too much fluid at the wound site can dramatically hinder the healing processes and induce further clinical complications [11]. Moisture-associated skin damage can result as a consequence of numerous factors (physical, chemical and microbial) acting in concert or individually. In chronic wounds, moisture-associated skin damage can be exacerbated simply through prolonged contact with wound exudate. Protein degrading enzymes (serine protease, elastase and metalloproteases), neutrophils and proinflammatory cytokines are typically present at high concentrations within wound exudate and can be considered to be a 'wounding agent' in its own right when left in contact with peri wound skin for excessive periods [11,12]. Rather than aiding closure of the wound, excess exudates can result in wound enlargement. The stalling of wound healing inevitably leads to an increased risk of infection with limb and life-threatening consequences.

Sensors for moisture measurement

Extensive research has been carried out into humidity/moisture based sensors for a wide range of agrifood, environmental, commercial and industrial applications but the translation of such technologies to the context of wound monitoring however brings a whole new series of challenges: disposability, low cost, biocompatibility, flexibility and a capacity to be miniaturised being among the more common. Milne et al. [13] pioneered the early development of wound moisture sensors and pursued the technology through to clinical realisation with the release of their Wound sense™ device. Their system involved embedding a disposable sensing strip (composed of two silver/silver chloride electrodes) within a conventional wound dressing with ac impedance measurements used to assess the moisture content of the latter. The device relied upon the wicking of the wound moisture into the dressing enabling electrical connection between electrodes. Whilst not strictly a humidity sensor, this early design enabled a measure of dressing saturation — with data presented directly to the nurse in an accessible dashboard display indicating the condition of the dressing from dry to sodden. The system lacked the sensitivity (and reversibility) needed for dynamic profiling of moisture fluctuations within the wound and the absence of autonomous reporting necessitated a high degree of nurse involvement. A number of designs have since arisen in an attempt to address the latter with wireless transmission of the moisture data to a smart phone/app [14]. However, it is clear that there remains much to be carried out to enable the idealised system advocated in Figure 1.

A range of analytical methodologies have been investigated in the development of humidity sensors (principally RH %) but there are several general electrochemical categories: resistive, impedance and capacitive sensors. These can be further subdivided depending on the type of the core sensing material with nano structured variants coming to dominate recent literature offering improved manufacturing processability and device sensitivity and these are the focus of the present review. The different approaches are briefly summarised in Table 1.

Resistive sensors

Resistive sensors RH sensors have a long history and, from a wound monitoring perspective, possess the advantage of requiring little in terms of supporting electronics. This is a critical point as, although much is often made of the small dimensions/flexibility of the sensor, the fact that the controlling electronics will also be in the vicinity of the wound and possibly located on the dressing or surrounding skin is often overlooked. The smaller the footprint of the controller/reporter, the less obtrusive the system and thereby minimises discomfort to the patient.

Sensing materials

Ceramic and metal oxide systems have been used extensively within industrial processes operating at

Table 1

Materials used in resistive humidity sensors.

Inorganics/oxides	Flexible	Range %RH	Sample	Reference
Polyimide with TiO_2 nanoflowers	Y	20–95	Breath	[15]
$CuMn_2O_4$/chitosan	N	20–95	NS	[16]
Cu/Cu_xO/polycarbonate	Y	0–55	Breath	[17]
ZnO/MoS_2	N	35–85	Air Quality	[14]
Nanoporous Nb_2O_5	N	40–90	NS	[18]
$ZnFe_2O_4$ spinel	N	30–90	NS	[19]
$NiPS_3$ 2D material on polypropylene	Y	11–97	Breath	[20]
Polymers/carbon nanomaterials				
PEDOT/PSS/Paper	Y	10–90	Artworks	[21]
Polyelectrolyte PMDS/ PPDS	N	10–95	Breath	[22]
PEDOT/PSS/GO/PET	Y	0–100	Air	[23]
MWCNT/ hydroxycellulose/ polyethylene terephthalate (PET)	Y	20–80	NS	[24]
MWCNT/cellulose/PAA	Y	30–95	Sweat	[25]
Gelatin GO	Y	0–95	NS	[26]
MWCNT/soybean oil and poly (ethylene glycol) methyl ether acrylate	Y	6–84	NS	[27]
MWCNT/Chitosan	N	30–100	NS	[28]

GO = Graphene oxide; MWCNT = Multiwalled carbon nanotube; PAA = Polyacrylic Acid; PET = Poly; PEDOT = poly(3,4-ethylenedioxythiophene); PSS = poly(styrene sulphonate); PMDS = poly(mercaptopropyl polyhedral oligomeric silsesquioxane-1,4-divinylbenzene-sodium p-styrene sulfonate hydrate); PPDS = poly(pentaerythritol tetra(3-mercaptopropionate)-1,4-divinylbenzene-sodium p-styrene sulfonate hydrate); PET = polyethylene terephthalate; NS = Not specified.

higher temperatures but have historically been known to be less responsive at low %RH — especially at the low temperatures expected within the wound environment. A variety of nano particle/nano oxide systems (Table 1), many incorporated into composite formulations, have sought to address some of these issues where the increased surface area and porosity of the materials aim to improve sensitivity.

Work by Jeong et al. [15] is particularly pertinent to the present discussion as they have successfully developed an inexpensive continuous roll-to-roll (R2R) polyimide print system in which nano-sculptured TiO_2 flowers are immobilised on silver interdigitated electrodes. The latter have been shown to be sensitive to moisture over a wide % RH range (20–95%) and possess the reversibility needed for dynamic measurements. Similarly, Hassan et al. [23] have developed an inkjet fabrication process on a flexible PET substrate but instead of a single sensor attempting to cover the entire RH range, they have adopted a three sensor configuration with each targeting a different RH region. It is easy to envisage both print processes providing ease of manufacture and at the volume required for disposable wound diagnostics but it could be argued that the 3-sensor system, whereas embracing a high degree of accuracy, is over-engineered for the problem at hand.

The response mechanism for many of the oxide systems is based on the chemisorption of water molecules onto the hydrophilic surface of the nanoparticles. At low RH, the former dissociate yielding hydroxyl groups adsorbed to the metal particle and mobile protons, resulting in high-charge carrier densities and hence larger current. As the RH is increased, multiple layers of water accumulate and form continuous dipoles and electrolyte layers between the connecting electrodes providing bulk conductivity. As the RH increases towards 100%, it can be fair to assume that the dressing is becoming saturated with moisture and, at that point (while perhaps not sodden) would signal a need for replacement.

Although the resistance of the metal oxide nanoparticle systems decrease markedly with increasing RH [15], the reverse is true in the case of many systems that exploit polymer composites encapsulating carbon nanomaterials (typically nanotube, graphene/graphene oxide). As the RH is increased, the polymeric binder swells, increasing the separation between the carbon materials (decreasing intertube/particle connection and percolation) and thereby increases the resistance. A critical element here is the need to have hydrophilic components that can readily facilitate the swelling process otherwise the resistance changes (and hence sensitivity) at low RH can be small. This has been countered by the use of hydroxycellulose [24], polyacrylic acid [25], various acrylated esters [27] and chitosan [28] all of which provide hydrophilic functionalities that induce significant volume changes upon exposure to low moisture levels.

Practicalities of the designs

Wounds will exhibit a wide range of morphologies and thus the ability of the sensor to conform to the contours of the damaged skin is critical. It can be seen from Table 1 that a number of sensors have utilised mechanically flexible substrates (driven in part by the increasing interest in wearable systems). Nevertheless, the work by Jeong et al. [15] is again significant in that repeated deformation of the polyimide substrate did not lead to any significant deterioration of the sensor response and could be particularly useful where the patient is ambulatory and the wound site liable to a degree of motion and distortion.

In most cases, interdigitated electrodes (typically, Au, Ag or Pt) have been used as the connecting electrodes, it could be anticipated that the use of laser-induced graphene to scribe the circuit connections [29,30] could yield further improvements in the manufacturing process (potentially reducing cost per sensor and increasing adaptability of sensor deign), and it is notable that such systems have increased across the sensing communities in recent years.

Biocompatibility will always be an issue and, although there can be suspicion over the use of some of the systems highlighted in Table 1, it is important to note that the sensors are embedded within the dressing and are unlikely to be in direct contact with the wound itself. Moreover, to ensure adequate adherence to a flexible substrate, protective films are invariably used to encapsulate the components (often with the cointention of aiding the adsorption of water) and thus effectively removed from interaction with the wound tissue.

Potential impact on practice

The provision of simple moisture sensing systems that can perform such duties autonomously could yield significant benefits in terms of optimising hard pressed community resources through the prioritisation of nurse visits. A study by Milne et al. [13] found that more than 40% of dressings were changed prematurely. It is generally accepted that the bulk of the costs associated with wound management is attributed not to the dressings and associated devices but rather to staff time and that the resources consumed in managing wounds in the community typically require 20% more visits to practice nurse visits and an increase of 104% community nurse visits to the patient [31]. Improved access to information technology (and hence sensor telemetry), enabling specialist input from remote consultations and greater educational support, have been cited as prioritising referrals and reducing unnecessary visits [32].

Conclusions

Despite many advances in materials and procedures, it must be recognised that, once applied, both conventional and 'advanced' dressings are essentially blind and an evaluation of their effectiveness in manipulating the wound environment remains subject to visual inspection by the attending healthcare professional only upon removal. The ability to monitor the moisture content and also detect when dressings need to be changed could be a critical addition to the community nursing tools.

Conflict of interest statement

Nothing declared.

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