Wearable Technology Based Smart Dressing for Effective Wound Monitoring–Correspondence

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Correspondence

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Skin wounds are a global healthcare concern, affecting nearly 1 billion people of the world's total population [1]. Owing to its morbidity and treatment payroll, it severely influences the patient's psychology and social milieu [2]. Any disruption in the anatomical structure of skin induces a wound, which may damage muscles, tendons, and bone leading to osteomyelitis, septicaemia, and even death. Depending upon the healing time and pathogenesis, wounds can be acute or chronic. Structural integrity is retrieved in case of acute wounds [3], whereas chronic wounds get arrested in a specific phase of healing. Body responds to skin wounds through a dynamic and multistep process known as wound healing, which headways in five stages namely wounding, haemostasis, inflammation, proliferation, and maturation [4].

Traditional treatments of wounds rely on wound dressings, which can be of passive, interactive, advanced, and bioactive types. Passive ones provide insignificant barrier to physical stress, interactive utilise polymers to allow them to be permeable to gases and liquids, advanced ones are made using hydrocolloids and alginates and bioactive dressings contain biological scaffolds [5]. Dressings need regular replacement, which may lead to additional injuries, and they do not reflect the condition of the wounds' bed and their healing rate [6]. Biomedical sensors and wearable devices pave the way for monitoring the progress of wound healing and overcoming the drawbacks of conventional methods. The designing of wearable devices and biomedical sensors for wound monitoring is a herculean task, as they must be highly specific, cost-efficient, flexible, and biocompatible.

Biomedical sensors and wearable devices focus on the evaluation and diagnosis of several biomarkers to indicate the wound healing process. Biomarkers utilised are moisture levels, oxygen, glucose, lactate, interleukins, C-Reactive proteins, uric acid, pH, temperature etc. Variation in moisture levels impair the wound healing process: high moisture leads to bacterial proliferation whereas low moisture slows down the remodelling phase. Oxygen is another important biomarker as it is needed for deposition of collagen and epithelialisation. Oxygen deprived tissues deal with hypoxia, which slows down wound healing. Partial pressure for oxygen is 5–20 mmHg in non-healing wounds and 30–50 mmHg in normal cells [5,6]. Glucose: In patients suffering from diabetes mellitus (high blood glucose levels), skin wounds can become non healing due to effect on angiogenesis, fibroblast aggregation etc. pH of the exudate tells us the pH of the skin wound. Acute wounds are slightly acidic, however chronic are alkaline. Higher pH indicates atypical healing process and bacterial infection [7]. Uric acid levels can also be measured from the exudate. High UA levels slow down the wound healing by affecting the inflammatory stage, whereas low levels increase risk of bacterial infiltration. Higher temperature at the wound site is another biomarker and can be an indication of infections.

Wearable sensors are fabricated using three building blocks: the substrate, receptor probe, and recognition or output elements. Substrate materials provide mechanical properties like flexibility and elasticity and can be polymers, textiles, hydrogels, inorganics, and even paper. They can be of natural origin like hemp, silk, chitin, etc., although the most frequently used are synthetic polymers like PET (polyethylene terephthalate) and PDMS (polydimethylsiloxane). Another component is the receptor probe or the bio-recognition element [8], responsible for identifying the analyte to be detected. The events recognised by the probe are then converted into detectable signals by recognition or output elements [9].

Wound monitoring can be done using reusable electronics, comprising of a wound dressing, and monitoring system. It makes use of a solution-based bandage that can be painted as a thin layer on the skin. Oxygen level's underlying the skin can be mapped using the film's oxygen-dependent phosphorescence. It can also include a potentiometric polyaniline (PANI)-based sensor, implemented on a bandage strip to monitor pH levels as well as moisture levels. Another way to monitor the condition of a wound is by measuring the electrical impedance, which varies due to change in hydration levels. This includes a wound dressing consisting of an absorbent material designed to soak up wound exudate and a number of electrodes placed to administer an electric current and/or voltage to tissue close to the wound.

A flexible and smart phototherapy patch emitting light in the UV, visible, or infrared (IR) electro-magnetic spectrums is another system to monitor wound healing process. The feedback process of the patch with one or more sensors speeds up the healing process by exposing the wound to controlled light. It also monitors infection symptoms, treats bacterial infections, and wirelessly transmits data for storage and interpretation by the doctor. The patch can hold more than one sensor that can monitor moisture levels, tissue impedance, redness, and temperature of the area of wound. Another approach includes a dressing enclosure designed to cover a wound and maintain decreased pressure at the injury site. The microfluidic device may then include a sensor that may examine the fluid exudate for one or more analytes indicative of the degree of wound healing. A wound dressing creating a negative pressure at the wound site and utilising a flexible substrate and multiple sensors is another option. The sensors can include pH, temperature and pressure sensors connected to each other and to a controller electrically.

A smart wound dressing with temperature and pH sensors has also been developed. The flexible dressing involves a thermo-responsive drug delivery system, where Poly(*N*-isopropylacrylamide) (PNIPAM) particles are loaded in a hydrogel mat. The dressing also contains an electrically controlled flexible heater guided using a microcontroller, which helps process the information gathered by the sensors [10]. An

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Ultra high frequency- Radio-Frequency identification (UHF-RFID) based smart plaster is another system utilised for wound monitoring. It utilises hydrogel membranes to create smart plasters which can collect and transmit data related to loss of fluids from the wound. This plaster also responds to temperature and fluid uptake/release [11]. A wireless, battery-free smart bandage measuring temperature and humidity of a skin wound was also developed using the Near-Field Communication (NFC) and RFID technologies [12]. The smart bandage was prepared using photolithography fabrication process.

A study also involved the development of a completely integrated battery free smart wound dressing for closed-loop wound management. The flexible, wireless and double layered dressing features multiplexed systems, where the upper layer comprises of a NFC circuit and lower layer of biosensors to detect changes in pH and uric acid levels [13]. For real-time wound temperature monitoring, a double-layered wound dressing with integrated electronics has also been developed. The lower layer comprises of a UV-responsive hydrogel, and the upper layer contains a temperature detecting sensor and diodes that emit UV light [14].

Although improvements in the field of wound healing and monitoring combined with wearable biosensors have been made over the past 20 years, still there is need to overcome various impediments to meet the requirements of modern healthcare [15]. As wound is a three-dimensional structure, technologies that measure biomarkers and depict the microscopic components of an injury can help with diagnosis and monitoring of different stages of wound healing and wound infections. Another pioneering approach can be utilising materials that are flexible, self-healable, absorbable and can be easily linked to biosensors. Using inkjet, screen, and 3D printing technologies to produce affordable and effective wearable sensors is another innovative strategy. The regulatory aspects and provisions for wearable biosensors and devices must be addressed competently to prove their safety and effectiveness.

Consent

Not applicable.

Registration of research studies

Not applicable.

Guarantor

Talha bin emran.

Ethical approval

Not applicable as no animal study was conducted.

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The authors declare that they have no conflicts of interest.

Research registration unique identifying number (UIN)

1. Name of the registry: not applicable.
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3. Hyperlink to your specific registration (must be publicly accessible and will be checked): not applicable.

Data statement

All data are available in the manuscript.

Author contributions

Sanshita: Conceptualization, Data curation, Writing-Original draft preparation, Writing- Reviewing and Editing. **Hitesh Chopra:** Conceptualization, Data curation, Writing-Original draft preparation, Writing- Reviewing and Editing. **Inderbir Singh:** Data curation, Writing-Original draft preparation, Writing- Reviewing and Editing. **Talha Bin Emran:** Writing- Reviewing and Editing, Visualization, Supervision. All authors critically revised the manuscript concerning intellectual content and approved the final manuscript.

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