The Dermal Abyss: Interfacing with the Skin by Tattooing Biosensors

Katia Vega
MIT Media Lab
Cambridge, MA, USA
katiav@media.mit.edu

Nan Jiang
Harvard Medical School
Cambridge, MA, USA
nanj@mit.edu

Xin Liu
MIT Media Lab
Cambridge, MA, USA
xxxxxxin@media.mit.edu

Viirj Kan
MIT Media Lab
Cambridge, MA, USA
viirj@media.mit.edu

Nick Barry
MIT Media Lab
Cambridge, MA, USA
nbarry@media.mit.edu

Pattie Maes
MIT Media Lab
Cambridge, MA, USA
pattie@media.mit.edu

Ali Yetisen
Harvard Medical School
Cambridge, MA, USA
akyetisen@gmail.com

Joe Paradiso
MIT Media Lab
Cambridge, MA, USA
joep@media.mit.edu

ABSTRACT

The Dermal Abyss (*d-abyss*) presents an approach to biointerfaces in which the body surface is rendered as an interactive display by patterning biosensors into the skin to produce color changes in response to biomarker variations in the interstitial fluid. It combines advances in biotechnology with traditional methods in tattoo artistry. *d-abyss* is designed to use the aesthetics, permanence, and visible nature of tattoos to encode information. In the present work, we replace traditional inks with colorimetric and fluorescent biosensors that can report on the concentration of sodium, glucose, and pH in the interstitial fluid of the skin. We report the preliminary evaluation of these biosensors in an *ex vivo* skin model, assessing their visibility from the dermis. We describe different applications of *d-abyss* in the medical, lifestyle, and security domains. This work is a proof of concept of a platform in which the skin reveals information inside the body, tattoos form wearable displays within the skin, and the body's metabolism works as an input for the *d-abyss* biosensors.

Author Keywords

Skin interfaces; tattoo; biosensor; wearable display.

ACM Classification Keywords

H.5.m Information interfaces and presentation (e.g., HCI): Miscellaneous

ISWC '17, September 11–15, 2017, Maui, HI, USA

ACM 978-1-4503-5188-1/17/09$15.00
https://doi.org/10.1145/3123021.3123039

INTRODUCTION

The term cyborg was coined in 1960 to describe the advantages of a human-machine system formed from the implantation of electronic devices into the body [7]. Transhumanism espouses a similar integration but rather of a biotechnological nature: from modifying genetic codes to re-engineering the body and the brain [22]. Since the inception of these concepts, different communities have proliferated around the idea of modifying the human body with technology. Grinders, for instance, are biohackers who share protocols by which they implant devices into their own bodies, as well as those for conducting gene-based modifications [4].

For centuries, humans embraced body modification as a deliberate procedure for altering the appearance and form of the body [8]. These alterations came in many forms: tattooing, piercing, branding, cutting, binding, and implants. Over the last 30 years, tattoos have become popular in western culture; today, approximately 20% of Americans have at least one tattoo [26]. The idea is common in science fiction, too, in which often the use of "living" tattoos is foreseen. For example, a man with a tattooed body in which each design represents a future story of his life is featured in The Illustrated Man [6]; a tattoo has a voice in someone's mind in an episode of the X-Files [32]; and Futurama presents a tattoo that is both animated and speaks [1]. While both traditional and modern techniques reshape or recolor or relocate the skin, we are spurred to probe further: can traditional body modification techniques embrace technology and can the skin reveal changes inside the body?

We present an approach to answer this challenge through tattooing optical biosensors into the skin that can react with changes in the interstitial fluid. Chemical biosensors detect changes in physical parameters and biomarker concentrations in the human body for monitoring of health status. Some pop-

ular targets include blood pressure, glucose, lactate, skin temperature, and brain activity [15, 21]. However, silicon-based implantable sensors are not biocompatible and they cause discomfort which disincentive their development in medical diagnostics. Recent advances in biosensors have focused on wearable devices [11, 31]. Wearable biosensors offer safety, ease of development, comfort, and maintenance, but suffer from a lack of direct access to the compartments in the body containing the relevant biomarkers. *d-abyss* has the access of an implantable biosensor but the interactivity of a wearable device. We expect that, motivated by the potential of *d-abyss*, new biosensors could be developed to increase selectivity, specificity, durability, and biocompatibility.

RELATED WORK

One approach to create an interactive skin is to place electronics on the body. Utilizing nanofabrication technology, epidermal electronics [10] are configured into stretchable "skin-like" membranes. A wearable chemical sensor in the form of a removable tattoo captures biological data such as glucose [3], pH [2], and lactate [15]. In the DIY community, conductive inks and stickers are applied as a tattoo to create aesthetic electrodes [5, 16]. Beauty Technology makes use of cosmetics to hide electronics and applies them to human body such as skin, hair, and fingernails [30].

Another approach is to place electronics into the skin. Silicon electronics are embedded onto silk substrates for creating implantable medical devices [17]. Conductive threads with sensors and microfluidic components are sewn into the skin to detect information such as pH level [23]. Although device implantation still faces technical barriers due to biocompatibility issues, the study of these devices for medical procedures and communication methods, and in their social and ethical implications are investigated[14]. These electronics-based approaches open up new possibilities for wearables: direct contact with the skin can significantly improve biological sensing data, information could be displayed in novel forms and movements, and conscious and unconscious behaviors could be amplified and trigger different devices. However, it brings up many challenges such as biocompatibility with electronics, battery recharging, and the incompatibility between solid-static and soft body tissues [20].

Tattoos are strongly associated with a desire for self-expression, uniqueness, and personal style [29]. There are also tattoos that are implemented for functional reasons, such as ensuring the location of reported radiotherapy applications, identifying blood types, scar camouflage and medical identification for conditions requiring special attention [18]. There has been an interest in animating tattoos. Designers have made mock ups to envision aesthetic possibilities of interactive tattoos [24, 10]. 3 μm thick photonic devices were laminated onto the skin to work as LEDs [35]. Additionally, injectable fluorescent hydrogel beads have been developed for monitoring glucose in the body (fluorescence-based) for glucose monitoring [28].

Integration of tattooing and biosensors are highly attractive to create new diagnostics, human-machine interaction interfaces, and cosmetic purposes. Biosensors are widely used in healthcare to quantify concentrations of biomarkers for application in medical diagnostics [19]. A typical biosensor consists of a biological or synthetic receptor that binds to a target biomarker to produce molecular changes or to create reaction products that are amplified and transduced through optical, electrical or magnetic readouts. For example, contact lens sensors offer an approach to diagnose ocular or metabolic diseases by measuring glucose, lactate, and pH [25]. Real-time biosensing devices allow monitoring human metabolism and activity. Wearable sensors on the skin provide a non-invasive strategy to assess perspiration analysis through monitoring sweat metabolites and electrolytes, and skin temperature. For example, a sweat-measuring electrochemical sensor was fabricated by combining flexible substrates with a silicon integrated circuit, which has enabled real-time monitoring of biomolecules through quantifying concentration changes in glucose, lactate and metal ions in human sweat [11].

DESIGN GOALS FOR *D-ABYSS*

The Skin as an Interactive Display. Changes in the skin's color already reveal ones diseases, emotions and even nutrition. By featuring tissue cells with interactive properties, the skin can change its color, light intensity, or structure to display information. Hence, the skin cells become a pixel screen to be decoded by the user, other viewers, or cameras. Integration of optical technologies with skin may allow camouflage or highlight such information dynamically.

Technology Indistinguishable from the Human Body. The hardware of current electronics-based wearables is noticeable. The introduction of biosensors as tattoos renders the technology seamless and personal. Liu, et al. identified the wearability factors of using electronics in Skin interfaces, i.e. aspects such as location, body movements and body characteristics, and device aspects such as weight, attachment methods, and battery life [20]. In *d-abyss*, the use of optical biosensors over electronics provides several advantages since they (i) do not require electrical power nor recharging, (ii) have the same weight and size of tattoos, (iii) are located inside of the skin making them permeable and insulated, and (iv) body movements, postures and stretches in skin will not affect their connectivity.

The Metabolism as an Input. Current devices offer different modalities for input including mechanical motion, touch, and audio. We propose the use of the metabolism as an input for *d-abyss*. Thus, the chemical reactions of the cells in the tissue will be driving the interaction. The interstitial fluid in human skin comprises different biomarkers (surrogate for blood) that could increase or diffuse colors depending on the individual's current state, their activities, and diet.

Body Modification. The prevalence and practices of body modification in different cultures is an indicator of humanity's desire of altering physical appearance. Tattoos, as one of the oldest body modification processes, are visual, aesthetic and permanent. Thus, *d-abyss* uses this well-known practice to create interfaces that provide information when the design changes colors or light intensity, that intertwine biosensors in aesthetic designs, and that are permanently monitoring the user's biomarker variations in interstitial fluid.

SKIN ANATOMY AND MATERIAL INTERFACING

Traditional tattoos involve injection of pigments with a carrier such as ethyl alcohol, water, propylene glycol, or glycerine using tattoo guns which typically contains a needle attached to a motor oscillating at $\sim 80 - 150$ Hz. After injecting the ink, the pigment is dispersed throughout the epidermis and upper dermis where it is incorporated within local fibroblast cells, concentrated at a layer below the dermis/epidermis boundary. The ink remains stable there for decades but can fade by migrating towards the dermis over long periods of time.

The interstitial fluid is the medium which surrounds the cells, enabling delivery of biomolecules, intercellular communication and removal of waste to flow between the skin and rest of the body. The fluid and solutes present in the interstitial come from the continuous exchange of plasma between blood and the walls of capillaries during the osmosis. Plasma in blood and interstitial fluid are comparable with both containing water, ions, and small solutes. The water solvent contains saccharides, electrolytes, lipid and proteins. Electrolytes such as sodium ions (Na^+) and chloride ions (Cl^-), bicarbonate(HCO_3^-), potassium (K^+), calcium(Ca^{2+}), and magnesium (Mg^{2+}) are present in interstitial fluid [27]. Measurement of analytes can provide crucial information about human metabolism.

In the present work, biosensors for basic metabolic electrolytes such as pH, sodium ions, and glucose were demonstrated as their measurements hold importance in medical diagnostics. The most fundamental metabolite in the body to monitor is pH. pH regulates the acid base homeostasis via bicarbonate and phosphate buffering, where the pH is maintained at 7.365; however, metabolic disturbances can regulate pH down or up, causing acidosis or alkalosis. Outside the physiological pH range; hence, its monitoring in the body has clinical utility at point-of-care settings. Sodium is the most abundant electrolyte in the body for regulating blood volume and pressure. The concentration of sodium ions in the interstitial fluid is tightly regulated from 136 to 150 mM and deviation from this range can be fatal for patients. For example, depletion of water from the body due to dehydration leads to hypernatremia and consequently seizures or coma. Additionally, the concentration of Na^+ ions has a close relation to hypertension. Hypertension can occur by having high concentration of Na^+ ions [12]. Thus, it is of great importance to monitor Na^+ ion concentration changes in the body. Moreover, glucose in interstitial fluid has been measured as a surrogate for blood glucose. Commercial glucose monitoring systems have found a wide use in diabetes management. The expansion of such monitoring systems to measure electrolytes and proteins will be a natural progression within point-of-care diagnostics.

BIOSENSOR PREPARATION

In clinical chemistry, metabolites in the body are generally monitored using electrochemistry. This technique involves measurement of current or voltage or a sensing probe to detects a metabolite. While electrochemical sensors are widely utilized in hospital laboratories, their application at portable devices has been limited as these sensors require electricity and frequent calibration. On the other hand, optical sensors have been demonstrated to be more practical as they have the remote detection capability without the requirement of electronic circuits and complicated transduction mechanisms. For example, chromogenic (colorimetric) sensors are widely utilized in urinalysis at point-of-care settings. Similarly, fluorescent biosensors provide a robust platform as they can be read using readily available light sources. Hence, the practicality, simple detection mechanisms, and low cost of optical biosensors could be used for rapid diagnostics in medicine and health care sectors. Fig. 1 shows the different changes of colors of the biosensors used in this work. We also present their preparation.

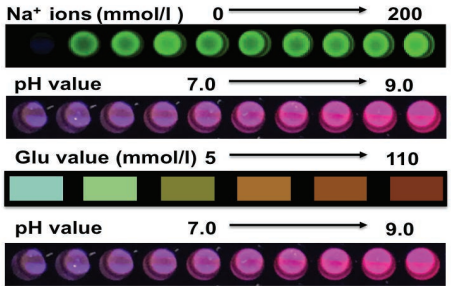

Figure 1. Colorimetric analyses and photographs of (a) fluorescent diaza-15-crown-5 in the presence of Na^+ ions, (b) seminaphtorhodafluor in the presence of H^+ ions in tris buffers using a smartphone at 25°C, (c) glucose biosensor from negative to 5, 15, 30, 60 and 110 mol-L^{-1} from [9], and (d) chromogenic pH biosensor changes in the visible spectrum.

Fluorescent Biosensors

Crown ethers are cyclic chelating agents that are specific to monovalent metal ions. We chose diaza-15-crown-5 (”sodium green”) as the chelating agent since it can selectively bind to Na^+ ions. Tissue pH is also vital in monitoring human health, and can be quantified by using seminaphtorhodafluor emission shift from yellow (λ=580 nm) to red (λ=640 nm).

Sodium

Fluorescent diaza-15-crown-5 (Sodium green) was purchased from Thermofisher and was diluted with Tris buffer (150 mmol-L^{-1}) and stored at -20°C. Sodium chloride (NaCl), tris hydrochloride (HCl, 99%), tris base (99.9%) were purchased from Sigma Aldrich. Tris-buffer solutions (150 mmol L-1, pH=7.4) were prepared using deionized water (DI water). Sodium green contains two 2’,7’-dichlorofluorescein dyes linked with a crown ether (a cavity), which selectively bind with Na^+ ions.[2] In the presence of NaCl, the specific 1:1 chelating ratio of the cavity in diaza-15-crown-5 and Na^+ ions increases the fluorescence intensity (Fig. 2 a). Increasing Na^+ ions concentration from 25 mmol-L^{-1} to 100 mmol-L^{-1} enhanced the fluorescence intensity 1.1 fold in the presence of diaza-15-crown-5 (25 μmol-L^{-1}) at 25°C (Fig. 2 b). A fluorescent plate reader (Synergy 2 Multi-Mode Reader) was purchased from BioTek. The colorimetric analyses of Na^+ ions and H^+ ions were carried out using a smartphone (iPhone 6S). NaCl and Tris buffer solutions were added to a 96 microwell plate (black) and the photographs were taken

under UV light excitation (365 nm, 5 mW-cm^{-2}). The colorimetric values from photographs were imported to ImageJ and analyzed. When Na^+ concentration increased from ion-free solution to 200 mmol-L^{-1}, the fluorescence intensity increased 1.9-fold (Fig. 2 a).

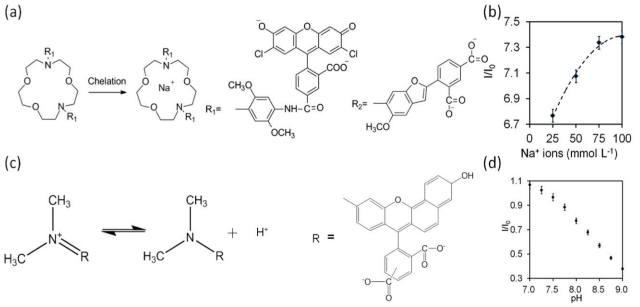

Figure 2. Na^+ ions and pH measurement using fluorescent probe in buffer solutions (150 mmol L-1, pH=7.4). (a) Chelating mechanism of diaza-15-crown-5; (b) Quantification of Na^+ ions at a constant probe concentration (25 μmol L-1) (n=3); (c) Principle of operation of sem-inaphtorhodafluor; (d) Fluorescent intensity readouts from tris-buffer solution as pH value was varied from 7.0 to 9.0 (n=3)at 25oC.

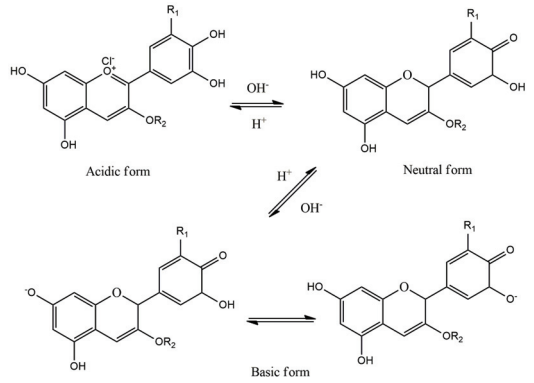

Figure 3. Chemical diagram of pH biosensor reaction

pH

Seminaphtorhodafluor (SNARF) was purchased from ThermoFisher Scientific. pH changes were measured using SNARF. When the pH value decreased, the SNARF molecule protonates; when the pH value increased, the molecule deprotonated (Fig. 2 c).[2] As the pH value of buffer solution increased from 7.0 to 9.0, the fluorescence intensity of SNARF decreased by 2.8 fold in the presence of SNARF (25 μmol-L^{-1}) (Fig. 2 d). Similarly, the fluorescence intensity increased 2.0 fold as the pH value of tris buffer increased from 7.0 to 9.0. The results demonstrated the colorimetric variations of Na^+ ions and H^+ ions in solution (Fig. 2 b).

Chromogenic Sensors

pH

The anthocyanin was derived from red cabbage extract and includes dextrose and citric acid serving as stabilization agents. Anthocyanins possess different molecular configurations that reversibly change based on the pH of an aqueous solution. When pH is below 3.0, the anthocyanins show predominant red due to the existing flavylium cation form. With the pH value of the aqueous solution increases, the flavylium cation form converts to carbinol psedobase and quinonodial base, resulting in color changes from red to violet (Fig. 3). The protonation and deprotonation process of anthocyanins produces chromogenic changes in the visible spectrum: pH 2 is red, pH 7 is violet, and pH 10 is blue.

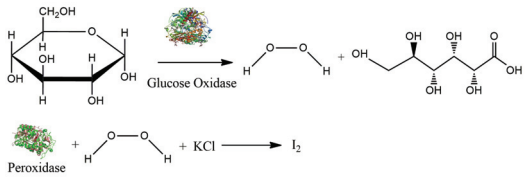

Figure 4. Chemical diagram of glucose biosensor reaction

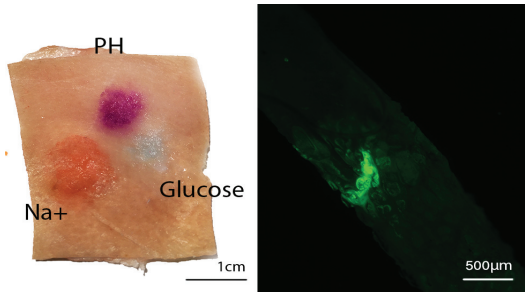

Figure 5. Biosensors injections. (a) Lateral injection of pH, glucose and sodium. Scale bar= 1 cm, and (b) vertical injection of fluorescent sodium. Scale bar= 500 microns.

Glucose

Glucose biosensors were extracted from reagent strips (Rapid Response Urinalysis) which is composed of: 1.5% *w/w* glucose oxidase; 0.5% *w/w* peroxidase; 10% *w/w* potassium iodide; 75% *w/w* buffer; 13% *w/w* non-reactive ingredients. This biosensor is a two-part reaction in which glucose within interstitial fluid undergoes an oxidation reaction with glucose oxidase to produce gluconic acid and also reduce oxygen to hydrogen peroxide (Fig. 4). In the presence of potassium iodide, the hydrogen peroxide reacts with peroxidase to produce iodine, resulting in a brown reaction.

INJECTION PROTOCOLS

We developed several injections in the skin in order to understand the visibility and functionality of the biosensors. Lateral injections emulate the post-healing tattoo by injecting the biosensor from the lateral side of the skin instead of the top. Vertical injections emulate the tattooing mechanism itself when the needle goes through the skin, deposits the biosensor in the dermis and the first reaction occurs with the interstitial fluid.

Sample preparation

Freshly-butchered pig foreleg was procured from a local market and small sections of skin removed to an approximate depth of 10mm. Samples were kept at -4°C.

Biosensor solution preparation

Four biosensors were examined in the current work: anthocyanin (chromogenic pH sensor), SNARF (fluorescent pH sensor), sodium green (fluorescent sodium sensor), and a glucose oxidase reaction complex (chromogenic glucose sensor). Anthocyanin was dissolved in deionized H_2O with a final concentration of 0.5% w/v. Sodium green was dissolved in 150mM Tris buffer (pH=7.4) at concentrations of 37.5μM and 50μM for the lateral and vertical injections, respectively. The chromogenic glucose sensor was sourced from commercial urinalysis test strips by incubating in dH_2O for 2 hours at 37°C at a relative concentration of 8 strips per milliliter. SNARF was dissolved to a final concentration of 25μM and 50μM in 150mM Tris buffer (pH=7.0) for the lateral and vertical injections, respectively.

Lateral injections

In order to visualize the biosensors, 50μL of solution was injected via 31-gauge 0.5cc syringes that had been manually inserted into the dermis ($\leq$ 4mm deep) of the pig skin from the side (in the plane of the skin). To maximize visibility, five close-packed injections were performed per condition. Injected skin samples were kept at 24oC for 10 minutes in order to ensure that biosensor reactions reached completion before imaging.

Vertical injections

In order to better understand the effect of injection depth on biosensor visibility and thus establish parity with existing skin labeling techniques, 31-gauge 0.5cc syringes were affixed to a height-adjustable stage positioned above a skin sample. By turning a knob, the depth to which the syringe penetrated the tissue was carefully controlled. After insertion to a depth of 2mm, 2μL of biosensor solution was injected. As with the lateral injections, 10 minutes were allowed to pass for the biosensors to reach equilibrium in their new environments. Samples were then frozen and manually sectioned so as to incorporate the syringe's performation (average slice thickness 1mm), then imaged.

Imaging

Samples with laterally-injected chromogenic sensors were imaged under normal indoor lighting conditions on an iPhone 6S. Laterally-injected fluorescent sensors were imaged under UV light on an iPhone 6S. Cross-sectional images of vertical injection sites were captured on a Zeiss Axio Observer D1 fluorescence microscope at ISO 1600 and exposure time 1/15s. For sodium λ_{ex}/em: 507/532 nm.

Results

The lateral injections show the visibility of the biosensors when deposited within the dermis, simulating the appearance of a tattoo post-healing. During the lateral injection process, each biosensor was visible from the surface. Fig. 5a. shows the lateral injection of the chromogenic pH biosensor. It changed color from pink to blue due to the pH concentration shift from 7.0 to 7.4 (ex vivo skin pH). Fig. 5b. shows a representative result of the vertical injection of the fluorescent pH sensor. The vertical injections demonstrated the depth profile of the biosensor penetration (in red). Fig. 6 shows the colorimetric and fluorescent readouts from biosensors as the concentrations of the analytes were varied in *ex vivo* skin. Fig. 6a shows the tattooed chromogenic glucose biosensor in pig skin without glucose solution. Fig. 6b illustrates the same biosensor in the presence of 10 mmol/L glucose solution. The pH sensors were also utilized in *ex vivo* studies. Fig. 6c shows the chromogenic biosensor at pH 8.0 having magenta color; however, when the pH was decreased to 7.0, the color shifted to pink (Fig. 6d). Additionally, the fluorescent probes were tested *ex vivo*. Fig. 6e-f shows the tattooed fluorescent diaza-15-crown-5 sensor in skin in the presence of 100 mmol/L Na+ ions under visible light and UV light, respectively. Fig. 6g-h shows the fluorescent seminaphtorhodafluor sensor in the presence of pH 8.0 in skin under visible light and UV light, respectively. Following the same protocols, a tattoo artist created designs with tattoo inks and the biosensors (Fig. 7).

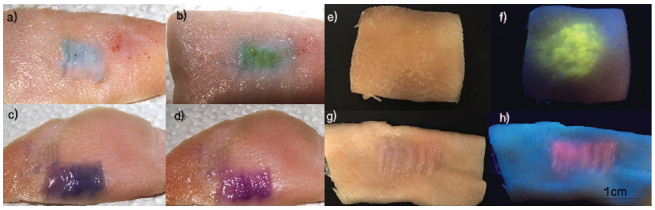

Figure 6. Biosensors tattooed in pig skin and the interaction under solutions. (a) Glucose biosensor, (b) Glucose biosensor with glucose, (c) Chromogenic biosensor at pH 8.0, (d) Chromogenic biosensor at pH 7.0, (e) Sodium green biosensor tattooed in skin under visible light, (f) Sodium green biosensor tattooed in skin under UV light excitation, (g) Fluorescent SNARF sensor tattooed in skin under visible light, (h) Fluorescent SNARF sensor tattooed in skin under UV light excitation at pH 8.0. Scale bar= 1 cm.

APPLICATIONS

Monitoring health status

Diabetes: Diabetics require glucose levels to be monitored by piercing the skin, sometimes 3 to 10 times per day to draw blood or plasma. Glucose levels in the dermis have shown to be an encouraging sensing target as it possesses little variation among subjects, is heterogeneously distributed throughout the skin, and dermal glucose concentrations remain promisingly close to values from blood glucose. The volume of glucose in the dermis is typically 0.40 ml/g with a volume density of 44 percent water [13].

Dehydration: Extreme dehydration causes hydrostatic pressure in the kidneys to drop and can result in kidney impairment or failure, as buildup of nitrogenous wastes accumulate in the bloodstream. While thirst mechanisms can signal to the body when dehydration is prevalent at a particular instance, long-term monitoring can enable information within the skin to be collected, stored and analyzed. Utilizing *dabyss*, dehydration can be sensed using sodium fluorescent biosensors. Higher monotonic concentrations of sodium solutes are prevalent in tissues when water loss occurs - activating the sodium biosensor.

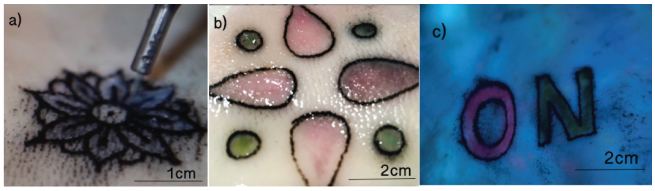

Figure 7. Designs made by a tattoo artist in *ex vivo* pig skin. (a) Tattoo artist designing with tattoo ink and chromegenic pH. (b) Chromogenic pH and glucose biosensors and (c) fluorescent seminaphtorhodafluor and diaza-15-crown-5 biosensors.

pH Balance: The body maintains a homeostatic state where pH is kept at a specific domain for the proper functioning of cells. Blood maintains a pH range of 7.385 to 7.437. Within the interstitum of the skin, pH is 7.35. Since interstitial fluid is comprised of a dynamic flux of solutes diffused from plasma within capillaries, pH can be an indicator of bodily responses upon local and systemic pathology. One such systemic pathology is diabetic ketoacidosis, a common condition in poorly-controlled diabetes in which a lack of insulin forces cells to rely on the oxidation of fatty acids for fuel.

Tattoo with Biometric Wearables

d-abyss provides relevant health information about the body. The tattoo may appear as an aesthetic design but from the lens of a health specialist paired with specialized software or decryption device - it may uncover underpinnings for an individual's health progress over time. Wearable devices and watches equipped with optical tools can also be used in conjunction with *d-abyss* for medical diagnostics. As an example, the different biosensors can be incorporated in one *d-abyss* design on a user's wrist. A camera-enabled smart watch monitors the tattoo. The watch emits a light at 507nm, causing the tattoo to reflect back a tattooed word which reads "ON" in a fluorescing green color at 532nm - indicating sodium levels. A flash of 530nm light enables the watch to read the fluorescent pH sensor as it reflects across a spectrum. The watch then snaps a photo of the tattoo to collect the sodium and pH level of the user. If implemented at scale, *d-abyss* has the potential to elucidate how such bodily fluid data in different users are affected by differences in medication intake, mood, lifestyle, or diet.

Maintaining a Culture of Health

Tattoo designs and symbols inscribed onto the body often signal information involving personal identity, tribe belonging and group affiliations. *d-abyss* can enable users to extend the function of self-expression and aesthetics of tattoos beyond personal representation, into a new medium advocating self-care and healthfulness. By utilizing the body's metabolic processes as an input for activating *d-abyss* tattoo displays, this can potentially extend signals of a user's health onto the aesthetic design of the tattoo. This incentives users to maintain care for their health and by extension, maintain desirable aesthetics of the tattoo. Chromogenic glucose and pH *d-abyss* can enable users to scribe symbolic and aesthetic designs on the skin while providing a quick glance to the user about their health. Moreover, there are numerous existent subcultures which incorporate a notion of identity, belonging and status with health.

Unique Identifiers

Bar and QR codes are computer coded designs which enable software recognition of arbitrary graphic symbols. Such designs can be encoded into tattoos to enable smartphone interfacing with links as well as skin-device interactions. For example, smart devices can mediate health data sharing in access to tattoo information. If the user permits, devices beam specific wavelengths of light on a fluorescent *d-abyss* to acquire access to information from a tattooed individual.

OPPORTUNITIES AND CHALLENGES

This section outlines the opportunities and challenges for designing these interfaces given the actual status of biosensors. Table 1 provides comparison between wearables or skin interfaces, and biointerfaces (*d-abyss*).

Wearables/ Skin Interfaces	***d-abyss***
Uses electronics	Uses biosensors
Into clothing, accessories or beauty products	Into the dermis
Close or on the body	Injected in the dermis
Maintenance requires hardware replacement or software update	Maintenance by injecting biosensors or laser removal treatments
Weight depends on the size of the device	Weight is based on the milliliters between the cells in the dermis
Size of the display could be limited by electronics and the skin characteristics	Biosensor could be applied all over the skin
Visualization on electronic displays. Higher resolution by the pixel's area	Visualization of color changes in the tattoo
Senses biodata or information in the environment (light, UV, sound)	Senses biodata
Requires electrical power or recharging to operate	Do not requires power to operate
Requires insulation	No insulation required
Depends on advances in electronics such as nanotechnology, battery, conductors	Depends on advances of biosensors such as color, reversibility, range of sensing, durability

Table 1. Wearability factors: Wearable Displays vs Bio Skin Interfaces.

In biotechnology. The utilization of tattooed biosensors as medical diagnostic devices are highly desirable as optical probes (i) can provide diagnostic data wirelessly, (ii) make sterile measurements *in vivo*, (iii) can provide real-time measurements of biomolecules for continuous monitoring [33]. Biosensors interfaced with wearable readout devices can detect a variety of biomolecules, and functional materials which could be "programmed" to change their properties such as shape, smell, and color[34]. However, current biosensors have some limitations that should be addressed before implantation. The range of colors and intensities of the current biosensors should be extended to enable higher-resolution information. Additionally, the optimization of the detection

range and the selectivity of the existing biosensors will accelerate their translation to the clinic or market. The safety profile of these biosensors must also be characterized, beginning first with cytoxicity assays and biocompatibility *in vitro* before progressing to *in vivo* animal studies to determine systemic biocompatibility, in terms of toxicity and interference with normal tissue function. Long-term *in vivo* researches will be needed for establishing the retention of the biosensors in the skin and to quantify biosensor diffusion in tissue. One potential research direction would be to conjugate the biosensors to polymeric microspheres through acrylate groups to prevent diffusion into tissues. However, phagocytosis of fluorescent biosensors / microparticles by the cells may present a confound. Fluorescent sensors present another challenge due to the increased likelihood of photobleaching over time.

*In interaction design.*There are several opportunities to use the skin as an interactive display. *d-abyss* offers interfaces of a similar size, weight, and flexibility to tattoos, rather than rigid electronics. A biosensor injected into the skin results in an interface that is insulated, permeable, and stretchable. In this environment exist a multiplicity of medically relevant compounds that can be used as an inputs in the *d-abyss* platform. Scarification, subdermal implants, and bageling are practices that are visible and permanent but do not have the colorful property that tattoos enjoy. Future projects could use shape modification biosensors in combination with those practices or skin treatments (e.g., henna, cosmetics and creams).

In its functionality. The time response in devices that interact with biosensors are different than the ones' with electronics. An immediate response is expected when a button is pressed or a screen is touched. *d-abyss* relies in the changes of the biomolecules for triggering the interaction. Another difference is the input method. *d-abyss* biosensors used the metabolism as an input. However, it could also explore the use external factors as input such as biosensors that change colors with temperature or pressure biosensors. Tattoos could be placed in any part of the skin, but the accessibility to them for visual monitoring needs to be considered. Biosensor tattoos could compatible with smartphones, cameras and other wearable devices to collect and measure the concentration values. Design aspects could be considering when tattooing biosensors: they could be filled with different biosensors for displaying different biodata in the same tattoo, it could be filled with both, traditional inks and biosensors, in order to encode or highlight data. The designs could be text that appears and disappear, images such a sunset that fades out and encryption codes such as QR codes.

CONCLUSION

The aim of this project is to create an interactive display within the skin in order to reveal internal changes in the body. The Dermal Abyss (*d-abyss*) is an exploration in the use of biosensors as tattoos for extending the sensing capability of the skin. A traditional tattooing practice was used for hiding technology within tattoo designs. This paper shows the potential of tattooing biosensors in the skin for applications in medical diagnostics, quantified self, and data encoding in the body. In our current proof-of-concept study, we demonstrated lateral and vertical injections in the skin to test the visibility and functionality of the optical biosensors in an *ex vivo* pig skin model.

In the same way that the wearables industry is integrating fashion practices in their development, we envision new partnerships between the biotech companies and skin professionals such as prosthesis experts and tattooists in order to embrace the idea of human-device symbiosis.

Future work will include research on new biosensors, body modification practices and interaction techniques. We expect that new biosensors will improve the durability, reversibility and range of colors. Different skin techniques such as henna, tanning and makeup will be explored for interactive skins and possible interactions with the biosensors tattoos. Other body modification practices can be used for creating different interfaces such as changing the shape of a dermal implant. Interaction with other devices and cameras can improve medical diagnosis and encryption.

REFERENCES

1. Amy Wong, 1999. Accessed: 2016-08-09.
2. Bandodkar, A. J., Hung, V. W., Jia, W., Valdés-Ramírez, G., Windmiller, J. R., Martinez, A. G., Ramírez, J., Chan, G., Kerman, K., and Wang, J. Tattoo-based potentiometric ion-selective sensors for epidermal ph monitoring. *Analyst 138*, 1 (2013), 123–128.
3. Bandodkar, A. J., Jia, W., Yardımcı, C., Wang, X., Ramirez, J., and Wang, J. Tattoo-based noninvasive glucose monitoring: a proof-of-concept study. *Analytical chemistry 87*, 1 (2014), 394–398.
4. Biohack.me, 2016. Accessed: 2016-08-09.
5. Bitarello, B., Fuks, H., and Queiroz, J. a. New technologies for dynamic tattoo art. In *Proceedings of the 5th International Conference on Tangible, Embedded and Embodied Interaction*, ACM (2011), 313–316.
6. Bradbury, R. *The Illustrated Man*. Simon and Schuster, 2012.
7. Clynes, M. E. Cyborgs and space. *Astronautics 26* (1960), 74–75.
8. Deter-Wolf, A., Robitaille, B., Krutak, L., and Galliot, S. The world's oldest tattoos. *Journal of Archaeological Science: Reports 5* (2016), 19–24.
9. Diastix. Urine test strips, 2015. Accessed: 2017-01-02.
10. Fairs, M. Design probes 2007 by philips design at dutch deign week, 2007. Accessed: 2016-08-09.
11. Gao, W., Emaminejad, S., Nyein, H. Y. Y., Challa, S., Chen, K., Peck, A., Fahad, H. M., Ota, H., Shiraki, H., Kiriya, D., et al. Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. *Nature 529*, 7587 (2016), 509–514.
12. Graudal, N. Population data on blood pressure and dietary sodium and potassium do not support public

health strategy to reduce salt intake in canadians. *Canadian Journal of Cardiology 32*, 3 (2016), 283–285.

13. Groenendaal, W., von Basum, G., Schmidt, K. A., Hilbers, P. A., and van Riel, N. A. Quantifying the composition of human skin for glucose sensor development. *Journal of diabetes science and technology 4*, 5 (2010), 1032–1040.
14. Heffernan, K. J., Vetere, F., and Chang, S. You put what, where?: Hobbyist use of insertable devices. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, ACM (2016), 1798–1809.
15. Jia, W., Bandodkar, A. J., Valdes-Ramírez, G., Windmiller, J. R., Yang, Z., Ramírez, J., Chan, G., and Wang, J. Electrochemical tattoo biosensors for real-time noninvasive lactate monitoring in human perspiration. *Analytical chemistry 85*, 14 (2013), 6553–6560.
16. Kao, H.-L. C., Johns, P., Roseway, A., and Czerwinski, M. Tattio: Fabrication of aesthetic and functional temporary tattoos. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, ACM (2016), 3699–3702.
17. Kim, D.-H., Kim, Y.-S., Amsden, J., Panilaitis, B., Kaplan, D. L., Omenetto, F. G., Zakin, M. R., and Rogers, J. A. Silicon electronics on silk as a path to bioresorbable, implantable devices. *Applied physics letters 95*, 13 (2009), 133701.
18. Kluger, N., and Aldasouqi, S. A new purpose for tattoos: medical alert tattoos. *La Presse Médicale 42*, 2 (2013), 134–137.
19. Kumar, M., Ghosh, S., Nayak, S., and Das, A. Recent advances in biosensor based diagnosis of urinary tract infection. *Biosensors and Bioelectronics 80* (2016), 497–510.
20. Liu, X., Vega, K., Maes, P., and Paradiso, J. A. Wearability factors for skin interfaces. In *Proceedings of the 7th Augmented Human International Conference 2016*, ACM (2016), 21.
21. Lo, B. P., Thiemjarus, S., King, R., and Yang, G.-Z. *Body sensor network–a wireless sensor platform for pervasive healthcare monitoring*. na, 2005.
22. More, M., and Vita-More, N. *The transhumanist reader: Classical and contemporary essays on the science, technology, and philosophy of the human future*. John Wiley & Sons, 2013.
23. Mostafalu, P., Akbari, M., Alberti, K. A., Xu, Q., Khademhosseini, A., and Sonkusale, S. R. A toolkit of thread-based microfluidics, sensors, and electronics for 3d tissue embedding for medical diagnostics. *Microsystems & Nanoengineering 2* (2016).
24. Oskar and Gaspar. Ink mapping: Video mapping projection on tattoos, by oskar and gaspar, 2015. Accessed: 2016-08-09.
25. Phan, C.-M., Subbaraman, L., and Jones, L. W. The use of contact lenses as biosensors. *Optometry & Vision Science 93*, 4 (2016), 419–425.
26. Ring, C. M., and Cohen, P. J. Cryosurgery for tattoo removal. In *Dermatological Cryosurgery and Cryotherapy*. Springer, 2016, 609–610.
27. Scallan, J., Huxley, V. H., and Korthuis, R. J. The interstitium.
28. Shibata, H., Heo, Y. J., Okitsu, T., Matsunaga, Y., Kawanishi, T., and Takeuchi, S. Injectable hydrogel microbeads for fluorescence-based in vivo continuous glucose monitoring. *Proceedings of the National Academy of Sciences 107*, 42 (2010), 17894–17898.
29. Tiggemann, M., and Golder, F. Tattooing: An expression of uniqueness in the appearance domain. *Body Image 3*, 4 (2006), 309–315.
30. Vega, K., and Fuks, H. Beauty technology: Body surface computing. *Computer 47*, 4 (2014), 71–75.
31. Wan, L., Han, G., Wang, H., Shu, L., Feng, N., and Peng, B. Wearable sensor localization considering mixed distributed sources in health monitoring systems. *Sensors 16*, 3 (2016), 368.
32. x-files wikia. Never again, 1997. Accessed: 2016-08-09.
33. Yetisen, A. K., Butt, H., Volpatti, L. R., Pavlichenko, I., Humar, M., Kwok, S. J., Koo, H., Kim, K. S., Naydenova, I., Khademhosseini, A., et al. Photonic hydrogel sensors. *Biotechnology advances 34*, 3 (2016), 250–271.
34. Yetisen, A. K., Naydenova, I., da Cruz Vasconcellos, F., Blyth, J., and Lowe, C. R. Holographic sensors: three-dimensional analyte-sensitive nanostructures and their applications. *Chemical reviews 114*, 20 (2014), 10654–10696.
35. Yokota, T., Zalar, P., Kaltenbrunner, M., Jinno, H., Matsuhisa, N., Kitanosako, H., Tachibana, Y., Yukita, W., Koizumi, M., and Someya, T. Ultraflexible organic photonic skin. *Science advances 2*, 4 (2016), e1501856.