SKIN ADHESIVE EVALUATION FOR LONG-TERM WEARABLES: AN INDUSTRY COLLABORATION

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2. Body of Text

Executive Summary
Medical wearable devices, such as continuous glucose monitors (CGMs), insulin pumps, drug delivery systems, activity trackers, and electrocardiogram monitors, are being continuously optimized by their manufacturers for wear time, performance, size, and cost. Adhesive materials that are critical for the interface of medical devices with the human body must therefore keep pace with novel device requirements and feedback from users. For example, the promise of extended wear time cannot be realized without the availability of adhesive products designed for multi-week wear.

We set out to engineer a medical adhesive system that offers reliable 21-day wear time. We assembled and evaluated mock devices consisting of a polycarbonate disk bonded to a skin adhesive tape in a skirt-style construction. We then recruited healthy human informed-consent volunteers to wear a randomized selection of prototypes on the back of their upper arms and recorded the times of application and failure (when the prototype eventually detached). We also noted instances of skin irritation and itchiness throughout the 30-day study. Following that, we assessed reliability by analyzing the time to adhesive failure using Kaplan-Meier non-parametric survival analysis. The prototypes evaluated in this study exhibited excellent reliability and were well-tolerated with no irritation during wear. The results emphasize the importance of selecting the right adhesive and carrier for the application, and that wear performance is dependent on numerous factors including adhesive chemistry, environment, device design, device location, and skin properties.

Introduction
Medical wearable devices or “wearables” are worn on the human body or clothing, which allows for continuous, real-time monitoring of physiological functions for diseases such as cardiovascular disease, diabetes, and neurological disorders.[1] Wearables have enjoyed remarkable innovation through advances in batteries, electronics, nanomaterials, and computing software—and they continue to evolve. Consider how the size and weight of CGMs have decreased over the past decade, improvements made possible by advances in electronics and sensors. CGMs can now boast of longer duration in use, longer battery life, and better data management.[2]

During wearable device development, it is essential to balance the mechanophysiology at the interface of the device and skin, with the diverse fragility of skin. The skin is the body’s largest organ and is made of water, proteins, fats, and minerals with features of 10-1000 µm height—all of which impact device adhesion and wear time.[3] Keeping devices attached to skin for weeks at a time requires specialized adhesives.

Such adhesives need to allow sensors to perform as expected and monitor activity without interfering or restricting the user's movement. Additionally, these devices also must be conformable, breathable, and comfortable for the user, as quality-of-life requirements are necessary for device adherence.

Materials

This study evaluated wear time of skin adhesive tapes in combination with a tie layer tape. The skin adhesive tape is a single-coated, nonwoven carrier with a medical grade acrylic-based adhesive designed for 21-day wear. The tie layer tape is a double-coated, transparent polyurethane (PU) film with a medical grade acrylic-based adhesive on both sides. It is designed to adhere skin carriers to a rigid wearable device.

Each skin adhesive tape and tie layer tape combination was tested in a wear study trial with a mock polycarbonate device (Figure 1). Each mock device was an island-placed mock device bound to the skin adhesive tape by using the tie layer tape. This configuration mirrors the design of commercially available wearable devices, such as CGMs. There were no cover/overlay tapes used in this study.

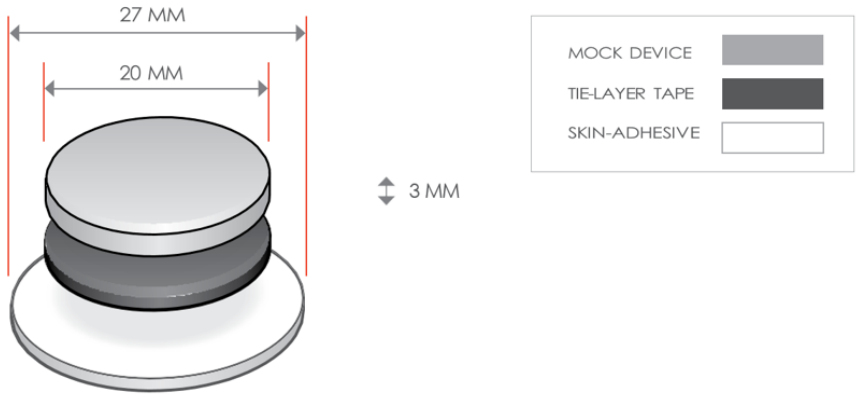

Figure 1. Illustration of the prototypical wearable devices evaluated in this study.

In this study, four different prototypes were evaluated which differed by skin adhesive tape coat weight (2.0mil vs. 4.0mil) and skin adhesive tape carrier material (polyester (PET) nonwoven vs. polyurethane (PU) nonwoven). These prototypes are outlined in Figure 2.

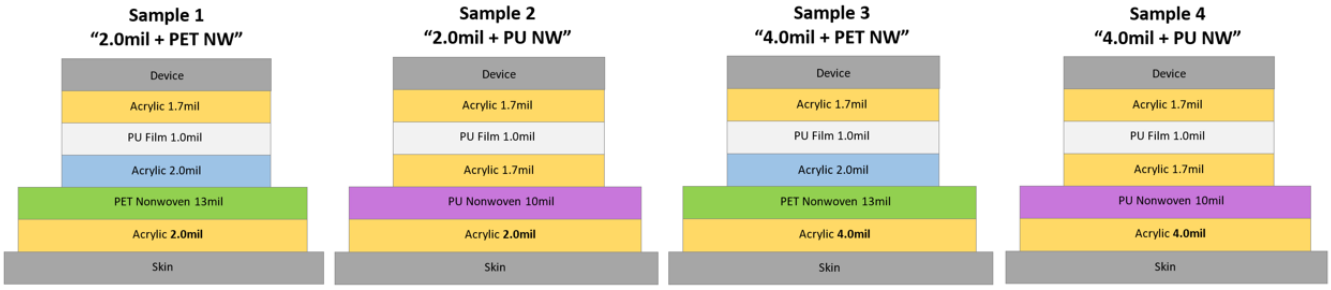

Figure 2. Diagram of the four prototype samples which were evaluated in this study.

Methodology

This wear study was conducted on healthy human volunteers. Each participant's consent was obtained prior to enrollment in the study. Skin contacting tape was verified for and passed biocompatibility testing per ISO 10993.

The researcher screened subjects by pre-determined inclusion and exclusion criteria. The inclusion criteria were: i) adults of at least 18 years of age and in good health, ii) willing and able to follow study directions, iii) willing to restrict swimming to 30 minutes at a time and no deeper than 3 feet underwater, and iv) willing to visit the researcher periodically throughout the study for performance assessments. Exclusion criteria were: i) pregnant and breastfeeding women, ii) acute or chronic skin conditions, iii) known skin allergies to man-made products, and iv) use of oral or parental steroids.

The study was conducted during the winter in Ohio. On the day of sample application (Day 0), the researcher assessed subjects' skin to ensure compliance with eligibility criteria. The subjects wore four prototypical wearable devices for up to 30 days (Figure 3). Devices were worn on the back of the upper arms (two devices per arm). Prior to device application, the skin of the test sites was cleaned with alcohol wipes (70% isopropanol) and left to dry for at least two minutes. Placement of the prototypes was randomized for unbiased distribution over the test locations across the participant pool.

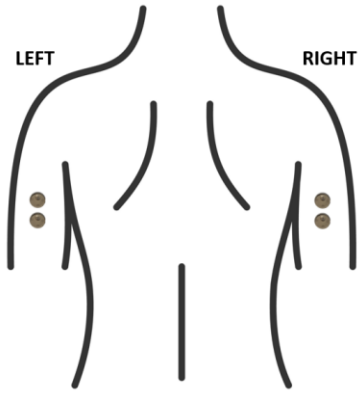

Figure 3. Illustration of prototype placement on the back of the upper arms.

Subjects were asked to wear the prototypes for a period of 30 days. Subjects were allowed to shower and exercise normally; the only restriction was for swimming which was limited to 30 minutes at a time and no deeper than 3 feet underwater per typical medical device manufacturer restrictions. Our researcher performed visual assessments of the prototypes every three days using quantitative grading scales, assessing the following characteristics:

- Percentage of the skin adhesive patch still adhered to the skin (edge lift).
- Appearance of the prototypes, including visual assessments of adhesive residue.
- Subject comfort (itchiness and irritation assessments, pain of removal grading).

The subjects reported the day and time when the prototypes detached from the skin. Where a prototype had fallen off prior to Day 30, the researcher documented the date, time, and conditions under which the prototype detached from the skin. The researcher then calculated the total elapsed wear times for each prototype based on the best available information documenting the removal time. Total wear time was defined as the elapsed time from when the prototype was applied until it became detached from the skin, either intentionally or unintentionally.

The researcher tabulated data and calculated basic summary statistics (mean and 95% confidence intervals). Minitab® statistical software conducted survival analysis. A non-parametric Kaplan-Meier technique was used to generate survival curves from the available data.

Results

Seventeen subjects enrolled in and completed the study. All subjects wore their prototypes until they fell off unintentionally or until the completion of the wear period. None of the subjects intentionally removed their prototypes because of skin irritation or any other reason.

Prototypes were randomized across four sites on the back of the upper arms, representing typical locations for wearable devices. Wear performance varied across the locations for each prototype, but there were no statistically significant differences in performance.

The total number of days the prototypes were attached to the test site was computed as the elapsed time between the device application and removal. Wear time of each prototype was plotted as a function of survival rate, as shown in Figure 4. Survival rate at 21 days was 29%, 53%, 71%, and 65%, for Samples 1, 2, 3, and 4, respectively. Average wear time was calculated to be 17.3, 18.9, 22.9, and 22.8 days for Samples 1, 2, 3, and 4, respectively.

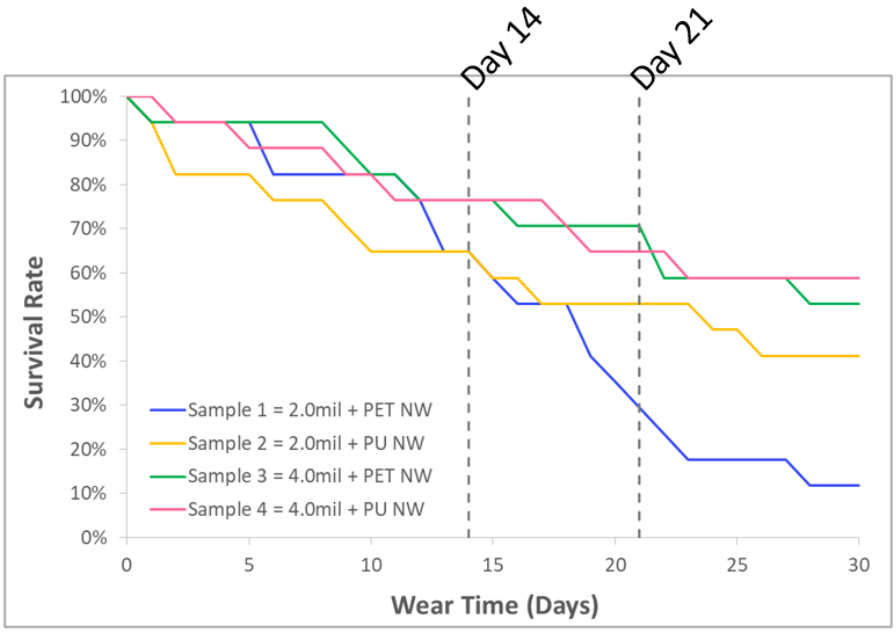

Figure 4. Survival curve illustrating the percentage of devices that remained adhered to skin as a function of wear time in days.

The 4.0mil prototypes (Sample 3 and Sample 4) displayed excellent multi-week wear and reliability as compared to the 2.0mil prototypes (Sample 1 and Sample 2). All prototype failures were seen at the skin layer interface, which indicates strong and robust tie layer performance (100% success rate). Adhesive residue on skin was rated as none to light (invisible but slightly sticky to the touch) for all samples after prototype fall-off or removal on Day 30.

Throughout the 30 days, all participants (100%) reported minimal to no itching for all prototypes. There was no irritation or other discomfort reported during the study's duration.

For subjects with a prototype remaining on Day 30, pain of prototype removal was reported on a scale from 0 to 10 via the Wong-Baker FACES® Pain Rating Scale. The pain rating was lower for the 2.0mil samples (rating 1.0-1.3 "none" to "hurts a little bit") as compared to the 4.0mil samples (rating 2.3-2.8 "hurts a little bit") but all ratings were well accepted for this application.

Conclusion

Recognizing the complexity of skin, a medical device's desired performance attributes, and user requirements are critical in selecting the right adhesive system. The proper balance of adhesion, cohesion, tack, and breathability is important because a need exists for secure attachment with easy removal. Inappropriate selections could lead to adhesion failure, skin injury, and/or device malfunction.

This paper summaries the results of four different skin adhesive tapes in combination with a tie layer tape as tested in a simulated wear application to characterize the product performance. For this particular adhesive system and geometry in this wear study, increased coat weight led to longer survivability and higher reliability with an average wear time of 22.9 days for Sample 3 (4.0mil + PET NW) and 22.8 days for Sample 4 (4.0mil + PU NW). Subjects found all prototype to be comfortable, with minimal to no itching, no irritation or other discomfort at any point during the study, low pain of removal on Day 30, and minimal adhesive residue left on skin after prototype fall-off or removal on Day 30.

The study showcases the importance of adhesive system selection for medical wearable devices. These skin adhesive tapes and tie layer tapes have distinct physical properties when tested in a controlled laboratory setting. Skin, on the other hand, is dynamic and varies from person to person. For these reasons, adhesive product testing via wear studies is an indispensable marker for success in medical wearables applications.

It is imperative to determine the right adhesive system early in a wearable medical device's development process. The adhesive selection is based on the device's size and shape, its intended wear time, location on the body, and the skin's condition. While the results from this study demonstrate excellent 21-day wear, the wear time for these products could extend beyond three weeks based on wear conditions, the user environment, and product design.

3. Literature Citations

1. Iqbal S, Mahgoub I, Du E, Leavitt M, Asghar W. Advances in healthcare wearable devices. *npj Flex. Electron*. 5, 9 (2021).

2. Didyuk O, Econom N, Guardia A, Livingston K, Klueh U. Continuous glucose monitoring devices: past, present, and future focus on the history and evolution of technological innovation. *J. Diabetes Sci. Technol*. 15, 3, 676-683 (2021).

3. Yetisen A, Martinez-Hurtado J, Unal B, Khademhosseini A, Butt H. Wearables in medicine. *Adv. Mater*. 30, 1-26 (2018).

4. Krejsa M, Luciano A, Butterworth D, Layser K. Clinical Methods for Evaluation of Wear and Pain in Medical Pressure Sensitive Adhesives. *Pressure Sensitive Tape Council Tech 40 Presentation* (2017).