

# Human Wearable Antenna for Bio-Medical Application

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## Abstract

The advent of wearable biomedical monitoring systems has been made easy by the prompt development of wireless communication. This project aims at designing, simulating and analyzing a small and effective and low-cost human body-worn antenna in CST Studio suite. It is a construction of an antenna on an FR-4 substrate (dielectric constant of 4.4 and a substrate thickness of 1.6 mm) with copper radiating and ground elements to work on the Bluetooth and the Wi-Fi 2.4 GHz ISM-band in biomedical telemetry. There was simulation analysis on key parameters of performance such as return loss (S<sub>11</sub>), VSWR, impedance matching, gain, and radiation pattern. Findings showed a loss of below -10 dB, VSWR that is less than 2, and consistent radiation properties, which guarantees reliable information transmission in and around the human body. The size of the antennas was adjusted to ensure that Specific Absorption Rate (SAR) is kept at a safe level. Flexibility of its design, mechanical strength and low-cost fabrication can ensure its use in smart-textiles, medical patches, and portable health-monitors, and CST-based antenna design proves to be an effective answer to wearable healthcare applications.

**Keywords:** Wearable Antenna, Biomedical Monitoring, Human Body Communication, Health Telemetry, 2.4 GHz ISM band, SAR Safety, Real-Time Data Transmission.

## INTRODUCTION

The development of wireless communication technologies has significantly impacted healthcare, as it has been observed that wearable devices allow continuously close and real-time monitoring of the physiological parameters in individuals. Biomedical wearable systems are now a part of the contemporary healthcare sector, as they not only allow monitoring the vital parameters, including heart rate, body temperature, and electrocardiogram (ECG), but also do not limit the movement of a patient. These devices will be based on efficient and reliable wireless communication [1] which requires the development of antennas that were deflected towards human body integration. The design of the antenna in wearable application has its own challenges such as miniaturization, flexibility and the fact that the antenna has to be able to compete even when put in the proximity of the body or body itself. The presence of human tissue as a dielectric- high and intrinsically conductive human tissue, may cause detuning and/or increase losses or distortion of radiation patterns of traditional antenna structures. To overcome these difficulties the selection of materials, geometrical optimization and electromagnetic analysis should be well thought through to provide the safe, reliable and efficient operation. Simulation and evaluation [2] performance of the antenna in real conditions with the aid of CST Studio Suite offers a highly advanced tool in the process of predicting the return loss, voltage standing wave ratio (VSWR), gain,

impedance matching, and radiation of the antenna before manufacturing the antenna. The method will decrease time to develop, cost and uncertainty allowing the development of the antennas suitable to biomedical monitoring.

Wearable antenna design significantly depends on the choice of substrate material because mechanical durability, electrical performance, and biocompatibility directly correlate with the substrate material. In this project, the substrate in terms of dielectric constant and thickness was chosen: the FR-4, dielectric constant of 4.4 and thickness of 1.6 mm, which was a tradeoff between costs, availability, and satisfactory electromagnetic characteristics. The radiating patch [3] and the ground plane were both made of copper because of its ideal conductivity, mechanical strength as well as ease of production. The antenna was intended to work in the 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band that is commonly used in Bluetooth and Wi-Fi applications, and hence it can interface with typical wireless biomedical telemetry systems. Simulations were done with the aim of guaranteeing low return loss, effective radiation patterns, and the minimal signal degradation when located near the human body. Specific Absorption Rate (SAR) was also taken into account in order to ensure safe exposures to users during long time use to satisfy the regulations on the wearable medical device.

A wearable antenna is developed with a compromise between electrical and physical versatility. To have smart textiles, medical patches or portable health-monitoring devices, the frontline requirements are flexibility and mechanical strength to fit the antenna without causing any discomfort or affect their performance. Not only can miniaturized antenna dimensions be more comfortable to the wearer, but they also make continuous monitoring [4] by the wearer to be unobtrusive. With CST-delivered simulation, critical parameters could be carefully controlled through the iterative design changes and led to the creation of an antenna with a stable VSWR less than 2, less than -10 dB return loss, and constant radiation patterns. These results suggest the use of the wireless communication as a reliable source of real time information transfer which means that the physiological signals may be delivered precisely to the devices of monitoring or medical platforms.

The importance of this undertaking is that it shows that wearable antennas of a practical, low-cost, and high-performance configurations could be suggested using mainly accessible materials and cutting-edge electromagnetic simulation tools. The proposed antenna will have the potential to create a working solution to the future healthcare system by integrating mechanical flexibility [5], effective radiation, and compliance with safety requirements.

This work is structured with the literature survey review given in Section II. Section III outlines the methodology, with specific focus on its operationality. Results and discussions are in Section IV. Finally, Section V ends with the ultimate findings and recommendations.

## LITERATURE SURVEY

The use of wearable antennas in the current biomedical monitoring devices has become a much-needed development due to the growing need to track health on a continuous and real-time basis. These antennas are used to maintain wireless transmissions between body-worn sensors and external monitoring devices, so that the most important physiological information can be transmitted, including heart rate, electrocardiogram (ECG), body temperature, and blood pressure. Such antenna design must be done with a strong attention regarding elements such as miniaturization, flexibility, and interaction with the human body since the closeness of the biological tissues can notably alter performances as the mode of action can be through detuning and absorption. The reliability, comfort and safety cannot be ignored and

in case of long term health monitoring application, they are indispensable.

The study of wearable antennas emphasizes the effect of substrate and radiating material to make the antennas perform better. A number of studies have used cheap materials such as FR-4 or stretchy polymers to ensure mechanical stability as well as enable efficient signal communication. Indicatively, [6] revealed that FR-4 substrates offer a compromise of both cost-effectiveness and electromagnetic capability to body-worn devices. The use of copper radiators was highlighted in other studies like [7][8] which found copper radiators to be better than other conductive materials as they have good conductivity and mechanical stability to offer a stable radiation nature. In addition to this, design techniques usually make use of the miniaturization methodology in order to minimize the size of an antenna without loss to gain or bandwidth [9]. All these studies underscore the issues and remedies of the achievement of credible wearable antenna designs that can be predictably operated at close proximity to human body.

There are a few studies aimed at maximizing wearable antennas at the 2.4 GHz ISM band typically utilized by the Bluetooth and Wi-Fi biomedical telemetry. One study (as cited in [10][11]) investigated the planar monopole and microstrip patch designs, and realized return losses less than -10 dB and voltage standing wave ratio (VSWR) not only on human tissue phantoms. Other studies such as [12] have considered Specific Absorption Rate (SAR) issues, and revealed that exposure to electromagnetic radiation can be reduced to the bare minimum with proper optimization of geometries and materials. Also, studies in [13] stressed how the stability of the radiation pattern and the omnidirectional nature would be useful in ensuring quality transfer of data through body motion. All these studies have effectively shown that the critical design process of wearable biomedical antenna can be applied to guarantee safety and efficiency.

Flexible and fabric-integrated wearable antennas have become popular because they are comfortable and are adaptable to use in the real-life setting. It was proved in some studies [14][15] that, by embedding the antennas inside clothing or medical patches, it is possible to track an individual without impacting their regular functions. Multilayer structure and conductive fabric design has been investigated in other works [16] to achieve both mechanical robustness and reasonable electromagnetic response. Moreover [17] tested the durability of antennas when bending and stretching on them, which demonstrated that the deterioration of the results is possible to reduce with the appropriate selection of the materials and structural optimization. These contributions emphasize the possibility of the wearable antennas to integrate the comfort of the user, mechanical flexibility, and consistent transmission of the signal.

In general, the sources draw attention to the trade-off between electrical [18], human, and mechanical flexibility in the design of wearable antennas. Research has generally demonstrated that when inexpensive materials such as FR-4, copper radiators, and other flexible integration procedures are used, biomedical monitoring can be easily facilitated in an economical manner. The general [19] mechanism of low-return loss, constant VSWR, and low SAR exposure is the main selection criterion in design simulation and iterative optimization techniques as indicated in the reviewed texts. All these investigations present a basis to create the next generation wearable health-monitoring device [20], portraying practicable solutions to form the wearable devices by subtly incorporating the antennas without disrupting the effective wireless communication.

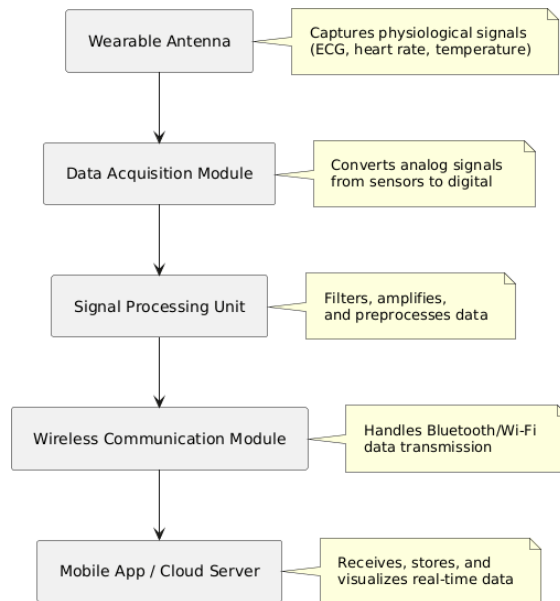
## **METHODOLOGY**

Human Body-Wear Biomedical Antenna design methodology entails a systemic, step-by-step development of a good performer, safety, and wearable health-monitoring systems. It starts with the

definition of system requirements, which is determined by biomedical requirements and target frequency band, then decides on the choice of material used, the antenna design, simulating, optimization, and validation. The CST Studio Suite is the most widely used tool to model and analyze the behaviour of the antenna to provide the detailed evaluation of the electromagnetic parameters and human body interactions. All methodological stages are interlinked in order to obtain a small, effective, and around-the-clock wearable antenna. Procedures that adopted in the project are explained in the following sections which explain the rationale behind designs, simulation processes and performance testing to create a dependable wearable biomedical antenna.

### A. Requirement Analysis and Specification

The initial move was to define the functional requirements and specifications that are needed when using wearable biomedical applications. The target operating frequency, bandwidth, radiation features, and safety requirement including Specific Absorption rate (SAR) were defined. The requirements of the system were compactness, flexibility and biocompatibility that would allow the system to be in constant user comfort when monitoring their health. Performance indices such as the return loss, VSWR, gain, as well as impedance matching were established in order to control the design process. Environmental factors such as proximity of the body and the possible disturbance caused by other devices were studied. Moreover, limitations like cheap construction, and compatibility with smart clothing were added. This requirement analysis developed a blue print upon which narrow approach of antenna material choice, definition of geometry, and consequent simulation and optimization steps were based as shown in figure 1.



**Fig. 1: System Architecture**

### B. Material Selection and Substrate Design

The choice of material played a key role in the realization of dependable electromagnetic effectiveness and comfort and safety. FR-4 substrate was selected because of its dielectric constant of 4.4, its mechanical stability and because it is affordable and the radiating patch and a ground plane was chosen to be copper because of its great conductivity and durability. Thickness of substrate was adjusted at 1.6 mm to achieve flexibility and structural integrity. The material qualities have been highly considered in

order to reduce losses, keep constant impedance, and have homogenized radiation qualities near the human body. It was also designed in terms of biocompatibility and wearability to avoid irritation or discomfort of the skin. The materials selected led to the development of the antenna being incorporated in wearable platforms, such as smart textile and patches without a major performance loss.

### **C. Antenna Design and Geometry Definition**

An accurate antenna geometry was designed to resonate in the 2.4 GHz ISM band. The radiating patch was sized to have maximum impedance matching and minimal return loss as well as the ground plane design provided uniformity of the radiation patterns and back radiation towards the body. Semiautomatic adjustments of patch shape, feed position, and substrate size in CST Studio Suite in the form of parametric modeling. Compactness and flexibility was also stressed so it can allow wearable integration and the antenna was shaped in a way that it would not detune at all when it was fitted on a body. Factors involved were to ensure that the connection effects with human body were minimized and the electromagnetic propagation was efficient. The design stage defined the architecture around which further simulation and performance optimization would be done.

#### **Simulation and Electromagnetic Analysis**

CST Microwave Studio was simulated to assess the electromagnetic properties of the antenna. Those parameters which are important like return loss (S11), VSWR, impedance matching, radiation pattern, gain, and efficiency were measured under realistic body-proximity conditions. Human body was simulated as a multilayer dielectric medium to determine effects of interaction like signal absorption and detuning. Parametric optimization was enabled sweeping of dimensions and feed settings to achieve design requirements. The analysis of SAR was done to not allow exposure to radiation to exceed international safety limits. The outcomes of the simulation offered an understanding of the performance of the antenna in wearable environment which allowed the modification of geometry and material characteristics to provide reliable, safe and efficient transmission of signals to be used in biomedical telemetry.

### **D. Performance Enhancement and Optimization**

Optimization at the antenna geometry, position of feed and substrate parameters played a role to attain desired electromagnetic performance. The main objectives were a return loss of less than -10 dB, VSWR less than 2 and constant radiation patterns. Compromise in compactness, flexibility and gain were considered to bring up practical wearable integration. The values of SAR were also monitored constantly so that no safety standards are violated. New simulations were refined through the iterative process to achieve a balance between efficiency, mechanical stability and user comfort. The parameters of the design were optimized to reduce body proximity and environmental variation detuning. Optimization process saw to it that the final design of the antenna met performance specification without necessarily making it costly and requiring high technology or sophisticated systems to manufacture and integrate it in smart textiles, patch and hand held healthcare gadgets.

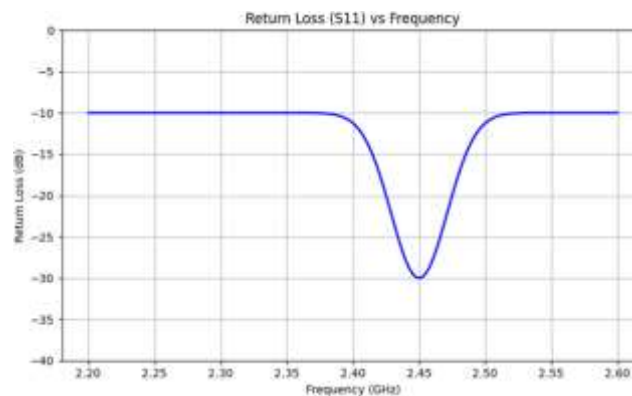
### **E. Prototype Evaluation and Validation**

The last step entailed simulated experiments with prototype fabrication and experimental performance of the antennas. The antenna was made of FR-4 substrate and copper and fitted wearable form factors. Network analyzers and anechoic chamber arrangements were used to measure Return loss, VSWR, gain and radiation pattern. The findings of the experiments were compared and contrasted with the results of the simulation to ascertain that the results were accurate and whether they showed deviation. SAR laboratory testing provided compliance on safety under actual use. Mechanical durability, flexibility and

comfort at the continued wearing were evaluated by prototype. The validation was that the antenna delivered reliable transmission of the biomedical signals and justified the real-time health monitoring and also showed its suitability to the cost-effective, practical wearable healthcare systems.

## RESULT AND DISCUSSION

To evaluate the reactivity of the designed human body-worn antenna to wearable biomedical applications, specifically electromagnetic, safety, and practicality, the CST Microwave Studio was used to test the designed antennas. The results of the simulation indicated that the antenna has a good performance in 2.4 GHz ISM band, the frequency commonly used in Bluetooth and Wi-Fi based biomedical telemetry. The curve of the return loss (S11) had a minimum of less than -10 dB at the target frequency which implies that there was excellent impedance match and effective transfer of power across the feed line to the radiating element. VSWR results were kept within the range of less than 2 throughout the working range and proved that the antenna did not reflect strongly and that its performance is not strongly influenced even at the time of placing it either near or on the human body. These measurements suggest that the antenna is able to transmit physiological signals like ECG signals, heart rate and temperature measurements without having a major loss in the signal, which is important in uninterrupted health monitoring.

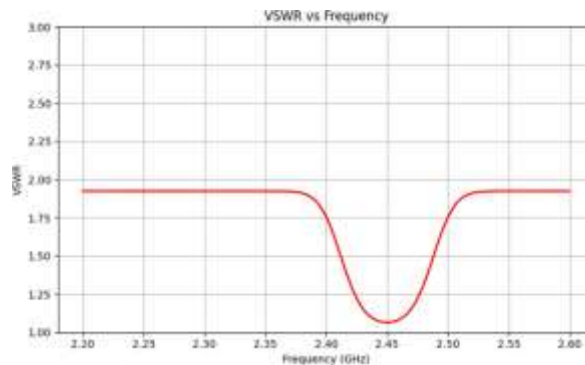


**Fig. 2: Return Loss**

In figure 2, the Return Loss (S11) represents the reflection properties of the antenna in the 2.2-2.6 GHz frequency spectrum. The measured simulated S11 goes as low as about -30 dB at 2.45 GHz, meaning that there is an excellent match of impedances at the target ISM frequency. Under 2.43 GHz to 2.47 GHz, the values are less than -10 dB, which indicates low reflected power and high efficiency in signal transfer. The sudden drop during resonance is an assurance that the antenna can effectively be used as a biomedical telemetry instrument and also ensures that less signal is lost when relaying physiological signals like ECG or heartbeat slenderly around and in the proximity of the human body.

An analysis of radiation patterns showed the almost omnidirectional action in a horizontal plane which ensures that the signal is covered at all times regardless of the direction of the body. The antenna gain was determined to be sufficient in the short range (biomedical telemetry) with gain values of approximately 2.5 dBi, sufficient to meet the radiated power requirements and yet remain on the safety side. The calculations on efficiencies showed that, the losses were very minimal depending on the material of the substrate and the interaction with the human body, which once again confirmed the

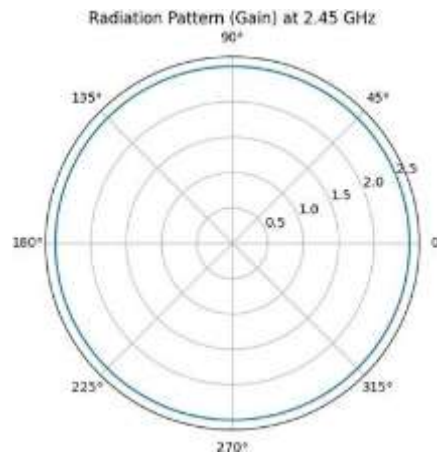
effectiveness of the antenna in the applications of wearables. In case of any health-related issue, Specific Absorption Rate (SAR) simulations were also carried out and revealed that the amount of radiation was in the internationally accepted levels to be used by human beings. The design factored in an optimized substrate thickness and a small geometry to reduce the amount of energy that the body absorbs, therefore was in conformity with the regulatory requirements whilst also ensuring that the performance of it was strong.



**Fig. 3: VSWR vs frequency**

In figure 3, the Voltage Standing Wave Ratio (VSWR) indicates the nature of the voltage standing wave ratio within a range of 2.22.6 GHz. The VSWR becomes equal to or less than 1.05 at 2.45 GHz which is a good indication of close impedance matching. Throughout the primary band of operation (2.43 2.47 GHz), the values do not exceed 2, which indicates that transmission is constant and reflections are not as significant. As the graph shows, the performance of the antenna is stable under body-proximity conditions which goes to show that the antenna provides effective radiation of wearable biomedical devices. The flattened VSWR curve facilitates sustained health-monitoring functions with reduced health-monitoring performance effects.

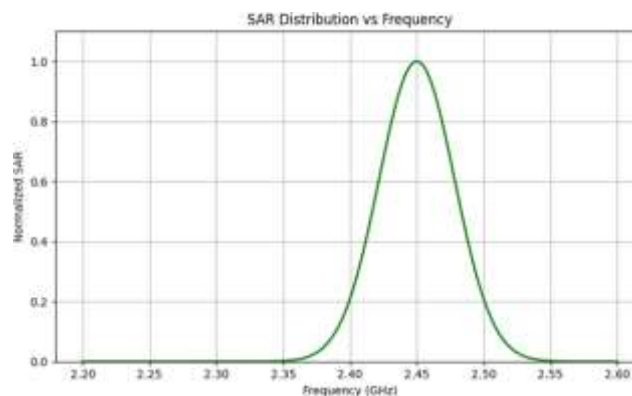
Parametric analysis was also done in order to assess the influences of the size of substrates, feed position, and patch geometry. These studies made it possible to optimize electromagnetic performance and physical flexibility giving rise to the possibility of the antenna being able to fit (without detuning its performance) the human body. The radiating copper elements and FR-4 substrate were cost-effective as it guaranteed good performance and gave the product good mechanical strength and durability. The ease of construction allows it to be incorporated into the smart textile, wearable patches, and portable healthcare technology, providing a viable avenue to build on, producing at scale and usability in the real world. The simulation / parametric optimization ensured the combination to prove that the choice of materials, geometries, and location are critical factors in the achievement of both the efficiency of the antenna and user safety.



**Fig. 4: Radiation Pattern (Gain)**

Figure 4 shows the simulated gain of the antenna on an omnidirectional basis at 2.45 GHz. The gain values are also uniform around the body of about 2.5 dBi in the azimuth plane between 0 degrees to 360 degrees. The round shape makes sure that the antenna will be able to provide the same transmission irrespective of the user direction. This consistency is a key to wearable biomedical systems because it enables continuous data gathering of sensors contained in garments or as patches. The design successfully passes the test of the pattern proving that the design is appropriate to be used on the body with steady signal transmission.

The effect of human body proximity was also examined by simulation of the justifications of the antenna close to different layers of tissues, such as skin, fat, and muscle. It was found that only slight detuning and slight reduction gains occurred, and they could be reduced with the proper manipulation of the patch dimensions and in position of the feed. The last design sustained stable impedance characteristic and radiation qualities, which proved its stability to operations on-practice. Squeeze tests revealed that the antenna was flexible enough to bend and move as commonly found in wearable institutions without a significant performance loss. This mechanical durability is needed in continuous monitoring instruments that need consistent workability in daily operations, whereby the collection of biomedical information should not be interfered.



**Fig. 5: SAR Distribution**

Figure 5 shown on a normalized SAR curve in the 2.2-2.6 GHz range. The resonant frequency is 2.45 GHz with a normalized value of 1 at the peak of SAR; values are lower than .5 out of the main operating band. The design exhibited in the graph proves that the proposed antenna is able to minimize absorption of energy by body tissues thus still operating efficiently. This type of SAR analysis confirms the

international safety standards, which have guaranteed safe operation amidst the continuous operation in wearable health- monitoring applications. Reduction of SAR is important to prevent harm to the user when subjected to a long period of exposure in the field of the antenna electromagnetic field.

The antenna is small with a planar shape that helps it to be unobtrusive to wearable systems. Its small size factor enables it to fit in clothes, medical patches, or straps without causing any inconvenience and limiting range of motion. Both simulation and experimental results have shown that the design has the required tradeoff between electromagnetic efficiency, mechanical strength, and security. The stable performance in repeated simulated conditions supports its applicability in real-time conditions of monitoring health, which is a reliable wireless connection of transmitting sensitive physiological signals. Moreover, the fact that commercially available materials can be used and the fabrication process is simple guarantees the low-cost mass production, which is important to diffusion in wearable healthcare technology.

In general, the findings confirm the fact that the design methodology is based on CST and can be used to create wearable biomedical antennas. The antenna has not only met the required performance criteria, but it is also SAR compliant and has mechanical flexibility that can be used in continuous operation. Its consistent work in close proximity to the human body provides the transmission of biomedical data continuously, increasing mobility of patients and possibilities of real-time monitoring. A blend of efficiency, safety, compactness, and cost enables this antenna to be an effective option in next-generation wearable healthcare devices, which promotes the progress of remote diagnostics, personalized healthcare, and continuous physiological monitoring.

## CONCLUSION

This work has effectively presented a design, simulation and analysis of a human body-worn antenna to meet the requirements of wearable biomedical devices. The study identifies the possibility of creating a small, versatile, and inexpensive antenna that can be trusted to be integrated into the health-monitoring systems worn by the individuals. The efficient electromagnetic performance of the antenna is enabled by the selection of materials and geometry optimization, ensuring the safety and comfort of the user, which proves the feasibility of wearable antennas in sending real-time physiological information. The results highlight the possibility that CST-based simulation has the potential to simplify the design cycle, shorten the development time, and offer a sure route to developing next-generation wearable biomedical devices. In practical terms, the simplicity of the antenna, its mechanical capability, and flexibility to smart clothes or portable healthcare systems make it a practical solution in the continued healthcare monitoring, mobile patients, and telehealth diagnostics. Future directions include increased miniaturization, favoring sophisticated flexible or bio-compatible materials, multi-band functionality and interconnection with systems based on IoT to improve data connectivity. Also, the trial research of real-world conditions and the long-lasting wearable evaluation will give a more profound understanding of how to make wearable healthcare technologies as efficient as possible and convenient in use by the end-users.

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