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Real-Time Hemodynamic Monitoring with Wearable Biosensors: Transforming Cardiovascular Management in Critical Care

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Annotation: Hemodynamic monitoring is an essential medical practice that enables healthcare providers to effectively assess a patient's cardiovascular health. This process grants critical insights into the progress of various diseases and the resulting treatment requirements that may arise. The application of this sophisticated monitoring technique to patients situated in critical care environments is especially imperative, as precise and accurate monitoring proves vital in facilitating the timely execution of life-saving interventions. Numerous commercial monitoring systems have been developed for this specific purpose, all designed to capture essential data in real time — a significant development that carries consequential impact on the efficacy of subsequent clinical decision-making processes. In fact, NASA recognizes hemodynamic monitoring as the greatest diagnostic advance of the twentieth century, which underlines the enormous significance of this system when it is applied to the comprehensive evaluation of an individual's overall health status. The insights gained from these monitoring systems not only inform immediate care but also lay the groundwork for long-term health strategies that can greatly improve patient outcomes.

1. Introduction to Hemodynamic Monitoring

Hemodynamics refers to the dynamics of blood flow, encompassing how the heart delivers oxygen and nutrients to tissues. Monitoring this parameter is critical in determining cardiovascular health; variations precipitate many diseases. Measurement involves analyzing various physiological parameters (e.g., blood flow variables, cardiac output, oxygen saturation, heart rate, blood pressure components, electrocardiogram [ECG]) and understanding their interrelations [1]. Historically, physicians relied on periodic, non-continuous clinical readings and observational assessments [2]. Subsequent developments yielded telemetric and implantable sensors capable of capturing periodic data through wireless transmission; though valuable, these devices remain largely limited to laboratory and clinical contexts and often fail to provide continuous real-time monitoring [3]. Unfortunately, sporadic data acquisition endangers health, since rapid intervention can be indispensable, especially during critical instances such as postoperative states, congestive heart failure episodes, and severe infections. Wearable biosensors constitute a promising alternative, enabling constant remote tracking of hemodynamic parameters. Coupled with data transmitters, these sensors facilitate prompt, spontaneous intervention whenever abnormal signals are detected. The emergence of mobile-health platforms further sophisticates information management, granting healthcare providers instant access to patients' physiological data.

2. The Importance of Real-Time Monitoring

Continuous and real-time monitoring of hemodynamic parameters has become crucial within the critical care setting. Hemodynamic monitoring facilitates personalized care through the early diagnosis of hemodynamic instability, guiding the appropriate selection of interventions, and supporting the titration of therapy toward individual patient needs [2]. Digital markers collected from hemodynamic data enable the tracking of patient status changes, allowing earlier intervention before clinical deterioration [4]. Continuous observation of fluctuations in blood pressure, heart rate, oxygen saturation, and temperature permits timely regulation of the dosage of vasoactive agents, fluids, supplemental oxygen, or antibiotics [3]. Moreover, real-time hemodynamic monitoring enables the detection of patient instability during transport within the hospital, such as during imaging studies or transfers to the operating room for emergency surgery.

3. Wearable Biosensors: An Overview

The field of wearable biosensors has witnessed a notable evolution, offering significant potential for improved personalized healthcare through real-time disease monitoring [5]. These devices have broadened the scope of physiologic sensing, extending beyond simple physical activity measurement to include analyte monitoring. Wearable biosensors can be categorized into wrist, head, clothing, foot, and somatosensory control devices. Thanks to miniaturization and technological innovations, wearable monitoring systems have become seamlessly integrated into daily life, especially wrist-mounted forms such as fitness bands and smartwatches. Evolving from basic accelerometer functionality, these devices now incorporate biometric sensors that communicate with electronic devices to relay physiological data.

Monitoring blood pressure remains critical in assessing an individual's health status. Innovative magnetic Hall sensor-based wearable devices mounted on the wrist capture pulse wave data without requiring cuffs and enable cuffless blood-pressure measurement. Similarly, photoplethysmography (PPG)-based heart-rate sensors capable of detecting variability are common in wrist-worn devices. These systems address motion artifacts encountered during routine activities and provide information vital for tracking general health conditions. Additionally, the development of non-invasive glucose monitors employing electrochemical methodologies to quantify glucose in interstitial fluids enhances the repertoire of biosensing capabilities.

Continuous biosensing technology has transformed patient management by affording real-time access to clinical statistics that inform diagnosis, monitor disease progression, and evaluate therapeutic response [6]. Biosensors combine a biological recognition element with a physiochemical transducer to selectively interact with target biomarkers. Such devices find application in timely disease diagnosis, drug discovery, and biomedicine. Skin-integrable and implantable formats supply detailed health status information with high temporal resolution. To address the requirements of continuous monitoring, biosensors must deliver high sensitivity and specificity, reliability, multiplexed measurements, and biocompatibility. Contemporary clinical approaches, relying on snapshot laboratory data, suffer from reproducibility challenges and lack the capacity to track symptom fluctuations between visits. Remote monitoring technologies have proven effective for managing chronic and acute diseases in resource-limited environments, also reducing associated healthcare costs. Portable and laboratory-independent surveillance of maternal and neonatal health parameters further underscores the utility of biosensor platforms. The military domain benefits from these lightweight, low-power, skin-conformable devices that provide continuous physiological assessment to safeguard performance and well-being. Continuous metabolite monitoring systems, capable of capturing clinically relevant trends, promise to enhance medical care in diverse settings.

4. Types of Wearable Biosensors

Real-time hemodynamic monitoring enables the continuous assessment of cardiovascular dynamics, thereby facilitating the timely diagnosis and management of cardiovascular diseases (CVDs), which remain the leading cause of mortality worldwide [7]. Traditional invasive cardiovascular monitoring techniques may cause vascular injury, require extensive infrastructure, and involve complex, costly sensors. Noninvasive monitoring techniques that permit wireless monitoring are therefore essential for the effective management of ischemia following cardiac interventions, as well as for the long-term evaluation of patients with CVD. Wearable devices integrate a multitude of sensors that acquire fundamental physiological variables, such as electrocardiogram, blood pressure, oxygen saturation, and heart rate variability [8].

Electrocardiogram (ECG) analysis is the prerequisite for cardiovascular monitoring. ECG and pulse signals primarily inform the evaluation of heart activities and the development of cardiovascular diseases. ECG and pulse sensors monitor heart status and provide omissions and accuracy in the development of CVD. Additionally, pulse signals are capable of measuring Seismocardiogram (SCG) and Photoplethysmogram (PPG) parameters.

Although blood pressure (BP) is mostly regulated within a certain range, long-term chronic diseases can cause severe damage, including stroke and cardiac arrest. Thus, the BP sensor is an indispensable element of cardiovascular monitoring [1]. Alongside electrocardiogram and BP monitoring, Pulse Oximeter (SpO_2) sensors offer a simple approach to monitoring oxygen saturation and pulse rate in arterial blood. Heart rate variability reflects the periodic beat-to-beat changes in heart rate. Wearable cardiovascular sensors with ultra-low power consumption, high sensitivity, and high linearity enable the frequency and waveforms of the heartbeat to be obtained. Sensors measuring the abovementioned parameters not only inform on cardiovascular activity but also on other physiological conditions such as stress, fatigue, and temperature.

4.1. Electrocardiogram (ECG) Sensors

Electrocardiogram (ECG) biosensors represent a pivotal technology in both healthcare and critical care settings. They continuously monitor vital cardiac parameters such as heart rate and electrical impulses, thereby facilitating comprehensive cardiovascular analysis. Advancements in telecommunications have enabled the deployment of sensor networks that stream real-time ECG data to clinicians, enhancing both in-hospital care and remote patient monitoring through telemedicine [7]. State-of-the-art wearable ECG devices, equipped with dry capacitive electrodes and driven right leg circuits, are designed for continuous monitoring and data transmission within body sensor networks. They have been successfully developed and tested for performance on both healthy subjects and cardiac patients [9]. These devices offer a viable solution for obtaining high-quality ECG signals conducive to long-term monitoring and telemedicine applications. Real-time classification methods integrated with these biosensors enable prompt detection of cardiac events, thereby improving patient safety. Furthermore, compliance with medical information standards such as FHIR promotes healthcare interoperability across distributed mobile infrastructures.

4.2. Blood Pressure Monitors

Continuous haemodynamic monitoring remains an essential part of patient care, although the technologies employed (basically pressure sensors and flow meters) have not advanced significantly during the past century. Wearable sensors that monitor blood pressure wirelessly and in real time may enable the early detection of cardiovascular pathologies and prevent critical episodes during surgery and in the intensive-care unit [10]. Advances in such devices, including a thin, soft, skin-like system that monitors artery blood pressure, carry the promise of transforming cardiovascular management in critical care [11].

Blood pressure measurement is among the most common and informative examinations in the practice of modern medicine. Blood pressure monitoring is an effective therapy-assessment means for hypertension and other cardiovascular diseases, and is indispensable in neurocritical, bariatric and paediatric patient care. Blood pressure can be measured using invasive or non-invasive methods. The cuff-based measurement is the most widely used non-invasive method, but continuous monitoring requires cumbersome assistive equipment. By contrast, cuffless technology enables continuous measurement with no intermittent time and causes no discomfort.

4.3. Pulse Oximeters

A pulse oximeter, a valuable wearable biosensor for continuous hemodynamic monitoring, measures the oxygen-saturation level of hemoglobin in arterial blood noninvasively. The development of smart-purple sensors compatible with these monitors enabled nonintrusive detection of SpO2 from the periphery [12]. This instrumental advance fostered wide acceptance of continuous monitoring in various sleep-related or clinical scenarios. Diagnostic devices that utilize pulse oximetry are currently undergoing rapid evolution, profoundly impacting clinical management of patients. The clinical application of these devices remains confined because of the unknown extent to which time-consuming experiments are required to confirm sensor performance. Long-term data collected under free-living condition usually suffer reliability and validity problems, limiting the implementation of wearable medical solutions for telecare and personalization; the confidentiality of data and privacy of the patient during remote and real-time monitoring is also crucial and must be respected.

A new class of affordable, portable, and lightweight health-monitoring devices has been made possible by recent advances in intelligent systems. These devices constitute a promising alternative to traditional clinical diagnostic tools for particular applications such as post-operative care and monitoring, chronic disease management, and long-term analysis of patients in remote locations. They are cost effective and provide noninvasive, nonintrusive monitoring without the need for constant professional attendance. Such physiological parameters provide unquestionably valuable health-related evidence enabling timelier and more accurate assessment of critical signs during daily living, resulting in getting early warning of potential health problems.

4.4. Heart Rate Variability Sensors

Heart rate sensors are frequently used to monitor vital signs in everyday life; nevertheless, heart rate variability (HRV) sensors provide greater insight into health conditions. HRV, the physiological variation in intervals between heartbeats, arises from the dynamic interplay between sympathetic and parasympathetic branches of the autonomic nervous system and serves as an index of autonomic function [13]. Common methods of measuring HRV include electrocardiogram (ECG) and photoplethysmography (PPG). Wearable ECG sensors employing textile electrodes (textrodes) have demonstrated performance comparable to traditional Holter monitors and can be integrated into garments to enable practical application [14]. PPG, prevalent in smartwatches and wristbands, derives heart rate by sensing blood volume changes in peripheral vessels. Although PPG and ECG signals exhibit strong correlation under static, controlled conditions, HRV parameters measured by PPG may diverge during mental effort or wrist movement. Real-time monitoring of heart rate and HRV has been adopted in several fields beyond healthcare. Tracking changes in HRV facilitates flow state regulation in artistic activities, while the perception of rhythmic and harmonic stimuli independently influences cardiac autonomic control as indicated by HRV analysis.

5. Technological Advances in Wearable Biosensors

Recent technological advances have significantly improved the accuracy and reliability of wearable biosensors designed for hemodynamic monitoring. These sensors track cardiovascular indicators such as electrocardiogram (ECG), blood pressure, arterial oxygen saturation, and heart rate variability to comprehensively evaluate the hemodynamic state of patients. The capacity to monitor multiple parameters simultaneously provides a holistic view of cardiovascular conditions, capturing nuances that single metrics might miss. Modern systems also incorporate wireless data acquisition and transmission capabilities, enabling real-time remote monitoring by healthcare professionals. Such functionalities not only facilitate continuous patient observation but also allow for integration with mobile health applications, thereby broadening the scope of clinical support. As a consequence, wearable biosensors are well-positioned to transform cardiovascular management in critical care settings, affording timely information to guide clinical decisions [7] [6] [8].

6. Data Acquisition and Transmission

Numerous wireless biosensing technologies with varying signal modalities enable the acquisition of continuous hemodynamic data from multiple body locations. Compact physiological sensors embedded in flexible substrates and worn on the skin accentuate wearability and adaptability in monitoring and telemedicine applications.

Near real-time bio-signals transmission can be achieved through integration with mobile health (mHealth) applications on smartphones [3]. System synchronization and communication capabilities facilitate simultaneous recordings from multiple subjects and support simultaneous and interacting remote sessions [15].

7. Integration with Mobile Health Applications

Mobile health applications have seen a significant surge alongside the heightened demand for mobile devices. These apps empower individuals to assess their health and wellness parameters autonomously and provide healthcare professionals with tools to streamline patient care, including teleconsulting, monitoring, diagnosis, and treatment [16]. Wearable biosensors frequently integrate with mobile technologies such as smartphones and tablets [17]. The coupling of biosensors and mobile applications facilitates the presentation of extensive physiological information, enabling comprehensive health assessments and timely decision-making in cardiovascular monitoring [18].

8. Challenges in Real-Time Monitoring

Advances in wearable technology have granted access to long-term continuous real-time monitoring of specific hemodynamic parameters, but not all clinically important variables can be reliably and remotely sensed at any point in time. Central venous pressure (CVP) and cardiac output (CO) provide essential physiological insights for guiding fluid resuscitation and vasopressor administration; their continuous measurement and transmission would not only reduce healthcare provider burden, but also enable rapid adjustments to treatment in response to evolving diagnoses. Estimation of these parameters via indirect measurements, derivable through wearable sensors that track metrics including blood pressure, thoracic landmarks, pulse transit time, cardiac time intervals, and various blood velocities presents an opportunity for precision outpatient monitoring [19]. Application in real-life critical care scenarios is hindered by concerns regarding data veracity and frequency, patient privacy, and medical adherence to formal clinical guidelines. Underpinning developments in modeling cardiovascular dynamics are imperative technological foundations for the successful monitoring of at-risk patients during the days and weeks post-discharge. Transthoracic echocardiography (TTE) and transpulmonary thermodilution (TPTD) are routinely used for CO measurement in hemodynamically unstable patients, although they require expert operators and are limited to episodic rather than ongoing measurement.

8.1. Data Accuracy and Reliability

The accuracy of vital sign measurements by wearable sensors depends on the clinical application, highlighting the need for evaluation in specific patient groups and settings [20]. The potential of wearable sensors is influenced by factors including which vital signs are monitored, measurement accuracy, data filtering, and susceptibility to movement artifacts. Heart rate emerges as the most accurately measured vital sign across devices. Respiratory rate (RR) measurements from devices like Everion show reduced accuracy when values deviate from normal ranges, which is concerning since abnormal RR is critical for detecting clinical deterioration; the VitalPatch sensor, positioned closer to the chest, may offer superior RR monitoring under such conditions. Oxygen saturation (SpO_2) is less frequently measured by wearable sensors and tends to be underestimated by devices such as Everion, thereby limiting clinical applicability. While most sensors record skin temperature, core temperature is likely more relevant for clinical assessment. Comprehensive evaluation of sensor performance should consider trending and diagnostic capabilities over extended monitoring periods. Validation efforts remain challenging due to discrepancies between wearable devices and reference instruments, although certain reference methods, like established RR monitors, provide more reliable benchmarks. Future research priorities include the development of optimal filtering techniques, efficient data storage solutions, and strategies to minimize movement artifacts, all aimed at enabling accurate long-term vital sign monitoring. [21][22][23]

8.2. Patient Privacy and Data Security

Continuous stream of biosensor measurements requires effective protection to preserve patient anonymity and data confidentiality while supporting data analysis and information extraction. Monitoring involves data of a sensitive nature, not only concerning individual patients, but also for larger surveyed populations. To minimize the dissemination of sensitive information, monitoring data must be carefully protected against malicious access by a large set of parties [24].

8.3. User Compliance and Acceptance

User compliance and acceptance represent crucial obstacles to the implementation of wearable sensor technologies in routine medical practice [25]. Noncompliance equates to nonperforming monitoring systems, resulting in degraded crucial support for clinical decision-making and compromised patient outcomes. Patients generally find wearable sensors acceptable; however, they experience particular challenges associated with comfort, inconvenience, and sensor removal. Further, distinct patient subpopulations and contexts of monitoring present specific challenges to implementation. Improved adherence and compliance with wearable biosensors thereby represent important objectives for the further development of these capabilities.

9. Clinical Applications in Critical Care

The clinical advantages of wearable biosensors for continuous monitoring of cardiovascular variables during recovery from surgery or acute decompensation have already been demonstrated [26]. Patients can be moved more rapidly from highly monitored care settings to less closely observed inpatient wards, freeing up expensive bed space for additional emergency admissions. Traditional equipment such as electrocardiographs (ECGs), chest and limb electrodes, catheter-based monitors, pulse oximeters and cuff sphygmomanometers are uncomfortable, difficult to set up and disruptive of therapy with dressings. Wearable sensors now provide a convenient alternative, enabling patients to be discharged to the community earlier without significant risk.

Development of automatic alerts is critical for future care [3]. Reductions in cardiac output, stroke volume and arterial oxygenation and increases in heart rate, respiratory rate, thoracic fluid and body posture are fundamental features of clinical deterioration and early indicators of shock. Early clinical trials of monitoring and alerting have been successfully conducted on adult general-ward surgical and medical patients. Recent studies have demonstrated the potential to improve long-term surveillance of chronic heart failure in the home. It is possible that tailored alarm criteria combined with continuous monitoring of haemodynamics may identify such deteriorations earlier and allow urgent intervention to prevent hospital admission.

9.1. Postoperative Monitoring

After cardiac surgery, intensive monitoring of hemodynamics and organ functions is critical. Early warning signs for complications are subtle and include increased ventilation, decreased heart rate, increased heart rate, and decreased cardiac output. Reliable monitoring depends critically on continuous measurements of vital signs. However, the immobility of critical care patients and continuous attention by healthcare staff, coupled with limited numbers of monitoring apparatus, make this monitoring challenging. A wearable sensing system capable of measuring vital signs continuously and wirelessly could unlock improvement opportunities. Postoperative patients can be burdened by thoracic drains, wires, and catheters, so minimizing their additional burden and maximizing monitoring capabilities is important. Non-intrusive and wireless monitoring devices promise benefits, but clinical requirements must be met for safety, security, and reliability [27].

9.2. Management of Heart Failure

In the contemporary clinical setting, many of the hemodynamic variables [classified in Section 9.1] can be measured continuously and noninvasively [3]. This is a decisive step that converts the concept of hemodynamic “monitoring” into that of hemodynamic “surveillance.” Arguably, the most challenging context is heart failure, where continuous measurement of cardiac output is commonly considered a Holy Grail that hospitals have yet to capture, despite it being achievable at the circuit level for several decades [28]. The aforementioned wearable bioimpedance-based monitoring device provides a means to achieve this goal. Cardiovascular function can be measured continuously before clinical outcome variables appear, offering indicators about what to do before the patient experiences further deterioration. Because it is based on sensors that do not require regular calibration, the system can be used for anywhere from hours to months without degradation in measurement accuracy. The continuous monitoring capability of the device—previously only available through invasive means within critical care environments—introduces the potential for effectively managing heart failure anywhere [29]. In this way, cardiovascular management reflects cardiovascular function not only at a given point in time but also over that period of time, instead of only providing the intermittent data currently recorded during infrequent follow-ups. This circumvents the challenges associated with imagining clinical data points during the intervals between visits, which is the scenario health professionals are usually faced with in practice.

9.3. Sepsis and Shock Management

Sepsis remains a leading cause of mortality worldwide, disproportionately affecting low- and middle-income countries (LMICs) where mortality rates remain high due to limited resources [30]. Continuous vital sign monitoring, a standard of care in high-income countries (HICs), is frequently unavailable in LMIC hospitals, resulting in infrequent vital sign measurements. The development of innovative, cost-effective wearable health technologies might enable healthcare providers in LMICs to detect early signs of patient deterioration and improve management. Most studies of wearable biosensors have focused on stable patients in HICs, with little research conducted in LMICs or among acutely ill patients. Adequate monitoring of septic patients remains a major challenge in the emergency department at Kigali University Teaching Hospital in Rwanda. Multimodal approaches to assessing perfusion status and resuscitation targets during septic shock incorporate bedside hemodynamic and perfusion assessment, arterial lactate measurement, and tests such as fluid responsiveness, vasopressor, and inodilator evaluations [31]. Frequent reassessment is critical for prognostication and to ensure the therapy remains adequate, with the goal of normalizing parameters such as capillary refill time (CRT) and central venous oxygen saturation (ScvO2). Rapid fluid challenge tests help determine fluid responsiveness and guide the resuscitation strategy.

10. Case Studies: Successful Implementation

Sensors attached to the body track vital signs and move information wirelessly to a monitoring system. These devices relay real-time biometric data to clinicians for use in a variety of patient care scenarios, including emergency services, post-operative convalescence, pre-term infant care, disaster medicine, and individual health assessment. A study of a wearable, wireless, multi-sensor device intended for monitoring blood circulation following free tissue transplantation affirmed the efficacy of a platform that can be adapted or customized to other clinical applications where regular monitoring is essential [32]. The combination of ultra-flexible, nanomembrane, wireless electronics anchored to functional medical-grade adhesives allows intimate coupling to the skin for non-invasive collection of high-fidelity datasets. Additional testing on 21 patients with residual limb “sockets” and 11 mild-to-moderate cases of venous, arterial, and diabetic foot wounds confirmed the same approach to be broadly useful for monitoring prosthetic use and wound healing [27].

11. Future Directions in Hemodynamic Monitoring

The current generation of wearable biosensors can acquire real-time signals and monitor multiple physiological parameters continuously. Wireless communication permits seamless data transmission to mobile health (mHealth) applications, facilitating real-time access by healthcare providers. Continuous real-time monitoring may serve as a companion to bedside hemodynamic monitors during the unstable stages of critical illness, and patients discharged from the hospital could remain under surveillance during their recovery. The next frontier in hemodynamic monitoring could lie in the utilization of artificial intelligence and machine learning algorithms to analyze prolonged streams of continuously acquired data, recognize subtle changes signaling clinical deterioration, and initiate early clinical interventions. Personalizing output measurements to account for specific patient characteristics may enhance the predictive power of these algorithms, potentially transforming critical care by improving the prevention, diagnosis, and management of cardiovascular disease through wearable biosensors [6].

11.1. Artificial Intelligence and Machine Learning

Integration of wearables and remote monitoring with artificial intelligence (AI) and machine learning (ML) is propelling cardiovascular care into a new digital frontier, with significant implications for heart failure (HF). Large volume and length of heterogeneous longitudinal data generated by remote monitoring devices necessitate automated processing and feature extraction strategies. AI/ML can discover informative markers and patterns that provide the basis for integrated outcomes prediction. AI/ML models built on supervised data and unsupervised machine methods have been applied in remote monitoring clinical applications such as early decompensation of HF, identifying patients at higher risk of sudden cardiac death, and optimizing therapies before presence of symptoms. Wearable devices integrated with AI/ML aim to detect pulmonary vascular congestion and clinical decompensation of HF earlier, resulting in timely therapeutic adjustment and consequently reduced hospitalization. For example, a pilot study with stage C HF patients used wearable seismocardiogram patches assessing mechanical vibrations of the chest wall, measured changes in signal similarity score over time, and investigated the possibility of identifying decompensated HF state and enabling preemptive treatment. Hierarchical clustering algorithm applied to electromechanical data further revealed three distinct phenotypes of myocardial dysfunction, providing potential insights into pathophysiological patterns of cardiac function and HF states [33].

11.2. Personalized Medicine Approaches

Applications in cardiovascular medicine involve wearable sensors for vital signs like electrocardiogram, blood pressure, pulse oximetry and heart rate variability. Such devices provide multi-parameter measurements integrated into mobile platforms that support tracking, data visualization, clinical decision-making and direct information sharing with health providers. Continuing development aims to enhance accuracy, reliability, long-term usability and ensure robust privacy and security measures [34].

The process of measuring vital signs in real time and transmitting raw sensor data at high frequency requires significant communication bandwidth. Edge computing addresses this challenge by performing on-board data processing and consolidating information before transmission. Efficient algorithms can run on wearable devices to enable continuous tracking of relevant physiological parameters while reducing data exchange needs, thus facilitating integration with mobile health applications in the context of real-time hemodynamic monitoring [35][36]

12. Conclusion

The complex interplay among blood pressure, heart rate, and flows is of clinical interest. Noninvasive remote monitoring of hemodynamic variables is crucial to optimize treatment opportunities and predict rehospitalization in patients with congestive heart failure. Characterization of cardiovascular state is also important in the context of resource shift to home-based care.

Current solutions provide continuous measurements of cardiac output and stroke volume, as well as other physiological parameters for prognosis and prevention of congestive heart failure. The core bioimpedance system is implemented in a CMOS application-specific integrated circuit, which operates as the analog front-end with a wireless communication section. The device’s parameters are remotely configured through a graphical user interface to measure complex impedance over a bandwidth of 1 kHz to 1 MHz. Evaluation was conducted on 33 patients with different heart diseases, ages, and genders. Comparison with Doppler echocardiography showed clinical equivalence.

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