International Journal of Analytical Mass Spectrometry and Chromatography, 2023, 11, 11-21
https://www.scirp.org/journal/ijamsc
ISSN Online: 2332-1776
ISSN Print: 2332-1768

Wearable Smart Sensor System for Medical Monitoring with an Assessment of the Level of Blood Loss and Pain Shock Because of Trauma or Injury

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How to cite this paper: Romanov, V., Galelyuka, I., Mintser, O. and Brondz, I. (2023) Wearable Smart Sensor System for Medical Monitoring with an Assessment of the Level of Blood Loss and Pain Shock Because of Trauma or Injury. *International Journal of Analytical Mass Spectrometry and Chromatography*, **11**, 11-21.
https://doi.org/10.4236/ijamsc.2023.112002

Received: April 9, 2023
Accepted: June 27, 2023
Published: June 30, 2023

Abstract

Blood loss in peacetime is mainly due to the normal menstrual cycle in women or diseases with surgical intervention. In wartime, blood loss in military personnel is a characteristic sign of a closed or open injury of the body during internal or external bleeding. Access to clinical care for wounded military personnel injured on the battlefield is limited and has long delays compared to patients in peacetime. Most of the deaths of wounded military personnel on the battlefield occur within the first hour after being wounded. The most common causes are delay in providing medical care, loss of time for diagnosis, delay in stabilization of pain shock and large blood loss. Some help in overcoming these problems is provided by the data in the individual capsule, which each soldier of the modern army possesses; however, data in an individual capsule is not sufficient to provide emergency medical care in field and hospital conditions. This paper considers a project for development of a smart real-time monitoring wearable system for blood loss and level of shock stress in wounded persons on the battlefield, which provides medical staff in field and hospital conditions with the necessary information to give timely medical care. Although the hospital will require additional information, the basic information about the victims will already be known before he enters the hospital. It is important to emphasize that the key term in this approach is monitoring. It is tracking, and not a one-time measurement of indicators, that is crucial in a valid definition of bleeding.

Keywords

Smart System, Blood Loss, Monitoring, Shock Index, Smart Wearable

Monitoring System

1. Introduction

The current level of development of information technology and microelectronics has already made it possible to master inexpensive systems of wearable medical smart sensors in industrial production and provide such systems not only for chronic patients, but also for sportsmen, military personnel, policemen, miners, and firefighters, who experience great physical and psychological stresses, and may also be wounded within their professional duties.

Requirements imposed on wearable medical monitoring systems of various origins are the following: they must be reliable, miniature and operate for a long time without replacing batteries. To meet these requirements, miniature wearable medical sensors and other sensors are used, along with microelectronic multichannel interfaces that are designed to connect the wearable sensors. These sensors capture and process measured parameters in real-time. These parameters include blood oxygen saturation, ECG, photoplethysmogram, blood pressure, heart rate and respiration, body temperature, skin impedance, and many others, which until recently were measured, as a rule, in clinical conditions. Monitoring of these parameters is important for elderly persons, patients in the postoperative period, for post-stroke and post-infarction patients who continue to be at risk. In addition, monitoring of medical parameters, including remote monitoring, as already noted, is important for those whose profession is associated with great physical and psychological stresses, as well as with the risk of serious injury or trauma. Therefore, remote monitoring of medical parameters outside the clinic is an important component of modern medical practice. It should be noted that now there are quite a lot of wearable medical monitoring systems in operation in the world, designed to monitor several medical parameters simultaneously. This can be monitoring of heart rate combined with monitoring of movement parameters, monitoring of heart rate combined with monitoring of skin impedance to determine the level of stress.

2. Aim

In conditions of hostilities and emergencies, it is necessary to provide victims with smart means to identify and quantify blood loss, as well as the level of pain shock resulting from injuries or traumas. Unfortunately, the market for wearable smart sensors and medical monitoring systems still lacks systems for assessing the level and rate of blood loss caused by trauma or injury.

2.1. Purpose of the Study

Suggest a new technology for the intelligent Internet of Things for early diagnosis of bleeding.

2.2. The Obtained Results and Their Discussion

The problem, first of all, is to recognize excessive blood loss, which is the cause of morbidity and mortality. The methods used to measure blood loss are divided into visual, direct measurement, gravimetric, photometric and others [1]. The most valid is a combination of direct measurement and gravimetric, however, the use of this approach is difficult in the field conditions. Photometry is the most accurate, but also the most expensive and difficult to use in wearable devices. Visual assessment of blood loss is so inaccurate that its further use in practice is questionable. Therefore, it is inappropriate to use it when choosing therapeutic actions [2]. Large blood loss can provoke severe hypovolemic shock and lead the victim to a rapid death. Accurate assessment of actual blood loss helps toprevent hypovolemic shock. Studies have shown that medical workers tend to overestimate small losses (<150 ml) and underestimate large ones (>150 ml), which leads to underestimation of vital parameters, conducting to instability in the functioning of the body as a whole [3].

2.3. Assessment of the Level of Blood Loss

An analysis of combat casualties from North Atlantic Treaty Organization (NATO) coalition partners during the International Security Assistance Force mission and Operation Enduring Freedom (OEF) in Afghanistan (2001-2021) and during Operation Iraqi Freedom (20 March 2003-1 May 2003) showed that most deaths occur before arrival at a hospital. In these fatal cases to the most appropriate medical treatment facility (MTF), bleeding has been identified as the leading cause of potentially preventable deaths.

These results highlight the importance of effective diagnosis and control of bleeding as soon as possible after an injury or trauma [4] [5]. The paper [6] concludes that civilian victims, usually with blunt injuries, have a "golden" hour, while battlefield victims with predominantly penetrating injuries have only 5 "platinum" minutes before intervention for the purpose of saving lives. In combat conditions, one of the most important aspects is that the proposed bleeding detection tool should be as simple as possible for using and based on the application of objective, quickly available data in conditions where it is not possible to use many research methods [7].

2.4. Algover-Bruber Index

One of the main tools currently used is the Shock Index (SHI), which corresponds to the ratio of heart rate (HR) and systolic blood pressure (SBP) and reveals acute hypovolemia and circulatory collapse [7] [8]. Shock Index is sometimes called Algover-Bruber index or I_{AB}:

$$I_{AB} = \text{HR}/\text{SBP}$$

where HR is heart rate, and SBP is systolic blood pressure.

The level of blood loss, expressed through the Algover-Bruber index, can be represented as following:

1) I_{AB} = 0.8 or less—blood loss is 10% - 15%.

2) I_{AB} = 0.9 - 1.2—blood loss is 20% - 25%.

3) I_{AB} = 1.3 - 1.5—blood loss is 30%.

4) I_{AB} = 2—blood loss is 40%.

The advantages of using the Shock Index are ease of use, using of readily available data, and specificity [9] [10]. At the same time, it is extremely important to know the basic individual values of the data, with which the comparison is provided. Other important information should be considered the limit values of SHI. Its threshold level is currently being discussed with the aim of standardizing the most reliable value with an assessment of the actual situation and patient needs, in addition to ease of use. There are, however, some discrepancies regarding the cut-off point, with some studies advocating an SHI ≥ 0.8 [11], others with an SHI ≥ 0.9, and finally some with an SHI ≥ 1.0 [10].

The classification of blood loss levels can be expressed in terms of circulating blood volume (CBV):

1) Mild blood loss is up to 1 litre (10% - 20% of CBV).

2) The average degree of blood loss—up to 1.5 litres (20% - 30% of the CBV).

3) Severe degree of blood loss—up to 2 litres (40% of the CBV).

4) Massive blood loss—more than 2 litres (more than 40% of the CBV).

Attention should be paid to a rather large scatter in the range of indicators when assessing the severity of blood loss. In addition, to assess the level of blood loss, it is important to know the initial CBV of the victim (before he was injured or traumatized), which depends on such parameters as weight, height, sex, age, etc. However, if the value of the initial CBV of the victim is not known in advance, then, as a rule, the average indicator, according to which the CBV in an adult healthy person is 6% - 8% of body weight [12]. Thus, the error in assessing the severity of blood loss according to the above indicators can be 10% or more. In practical medicine, there are many methods for assessing blood loss in real time. They can be divided into two large groups: direct and indirect. Direct assessment mainly includes various biochemical methods that are used in surgical operations. Outside the clinic, indirect methods are used, usually under the supervision of medical personnel. The use of wearable smart sensors and systems for assessing the severity of blood loss in real time is currently unknown to authors.

Motivations of the work according to [13] are following:

Improving the quality of life for people, associated with a risk to life.

First aid in 5 - 15 min on emergency.

Reducing the cost of monitoring and first aid.

Creating new collaborative models for clinics and ambulance service providers.

Main objectives of the work are following:

Supplementing regular monitoring by wearable smart-sensors and smart systems, and signalling on emergency conditions. Of course, it is not a new idea, but the new can be our measurement capabilities and personification of the system.

Implementing highly scalable service-oriented system for automated control of health risk identification and first aid for ambulance medical stuff, patients themselves, clinicians and management.

Integration of monitoring smart system with event handling, service time accounting/billing, feedback to emergency aid.

What is new of the work: first active aid; automated application of wearable injectors on emergency; including smart sensors for estimation of blood loss due to bleeding; application of wearable individual on-line capsule of memory with personal data of CBV, normal blood pressure, heart rate, etc.

So, if we use wearable means with personal data of CBV, normal blood pressure, and heart rate of injured in wearable smart system it will be possible to reduce the error of estimation of blood loss of the injured due to bleeding. To estimate blood loss, we need to measure in real time blood pressure and heart rate and calculate blood loss according to Algover-Bruber Index with a glance not average data but real medical parameters of injured.

Further refinement of this indicator is possible when considering additional parameters of the victim, namely body temperature, blood viscosity and the level of saturation with oxygen. However, in this case, these parameters must be measured synchronously with blood pressure and heart rate, and then the correction factor must be introduced into the expression to determine the Algover-Bruber index.

2.5. Integrated Microcircuits for Designing Wearable Smart System for Medical Monitoring with an Assessment of the Level of Blood Loss

Authors acquired a large experience in development and application of different systems and devices for medicine:

Development of miniature software-hardware complexes for clinical medicine, sport, labour, and military medicine as well as for personal use.

Application of the developed systems under various clinical and point-of-care test conditions.

Application of WHO international questionnaires.

Sufficient clinical database.

Interdisciplinary team of experts including professional hardware and software engineers, clinical medicine authorities and qualified medical cybernetics researchers.

When designing wearable smart monitoring systems, in most cases, interfaces of different types are used to measure different parameters, which leads to the use of several modules of the same type or integrated microcircuits (IMCs), each of which contains an analogy-to-digital converter (ADC), a processor, a secondary power supply and other similar units. All this complicates the monitoring system, and, most importantly, increases energy consumption and reduces its reliability during operation. This implies the conclusion about the expediency of using one universal interface to connect the required number of sensors to it.

Such universal interfaces are already available on the market of electronic components. These include the IMC of the ADPD4000/ADPD4001 family from Analog Devices, the functional diagram of which is shown in Figure 1. The interface makes it possible to connect 8 medical sensors; it contains an 8-channel multiplexer, two programmable gain amplifiers, two filters, two integrators, an ADC, a processor with memory and general-purpose interface unit.

With the IMC, you can measure the heart rate, the level of oxygen saturation in the blood. It can be used to collect, analyse, and process cardio signals. In addition, this IMC generates excitation signals for measuring skin impedance, as well as a reference voltage for electrodes when measuring biopotentials. The IMC does not require additional computing resources for the primary processing of the measured data. It provides for synchronization of measurement of different medical parameters to determine the correlation between them. The shape of the pulse wave can be used to determine blood pressure. The IMC integrates 14-bit ADC with a sampling rate of 1 MHz, processor with memory for data processing, LED drivers and excitation sources. For optical measurement of pulse waves, the ADPD4000 has programmable LED drivers. Another example of a microelectronic interface for wearable smart medical monitoring systems is the Analog Devices IMC ADPD188GG. With it, you can measure in real time almost all these parameters, including the oxygen saturation of blood.

2.6. Smart Medical Monitoring System

In general, if a smart medical monitoring system is designed to operate remotely, it includes a wireless data exchange module, as shown in Figure 2.

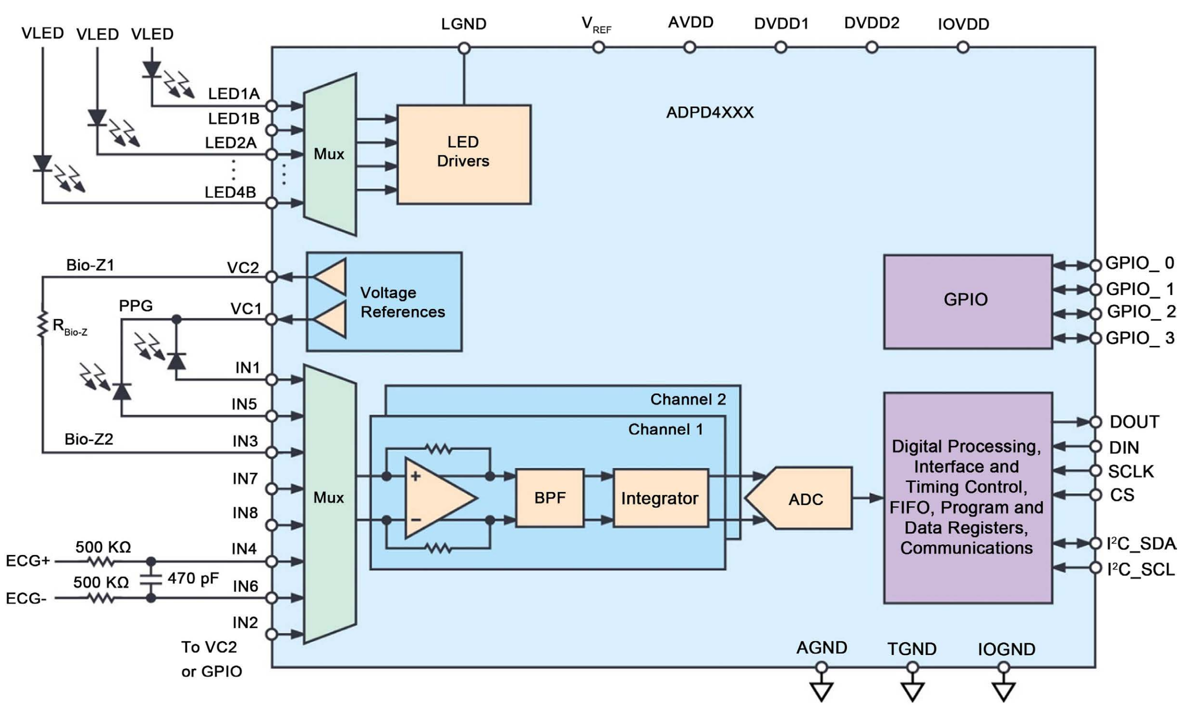

Figure 1. Functional diagram of ADPD4xxx interface.

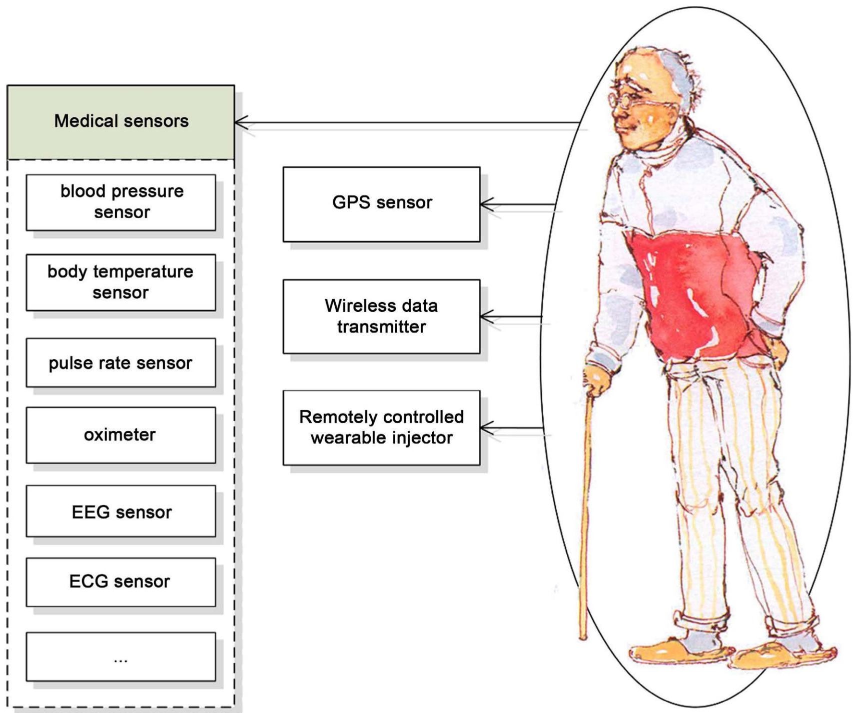

Figure 2. Smart wearable monitoring system.

Wearable sensors are connected to the data exchange module through the interface. In addition to transmitting data to a remote diagnostic centre, this module can support the management of wearable injectors that are designed to inject medicines on command from a remote medical centre. It should be considered that remote medical monitoring consists not only in the organization of wireless data transmission channels, but also in the organization and support of the infrastructure for the operation of the monitoring system. This involves organizing Internet services, storing, and protecting data in a remote server, creating application software, supporting the operation of a real-time monitoring system, ensuring long-term operation of sensors without maintenance and battery replacement. Currently, there are many standards and protocols for wireless sensor networks that can successfully use in medical monitoring systems. Among them, thereare the following: Bluetooth, BluetoothLE, Bluetooth Smart, IEEE 802.15.4, ZigBee, Thread, Wireless HART and others. An example of a smart remote medical monitoring system, that uses several data exchange protocols, is system, developed at the V. M. Glushkov Institute of Cybernetics of the National Academy of Sciences, the structure of which is shown in **Figure 3**.

Only one protocol can be used for network operation within the clinic, for example, ZigBee. In this case, all nodes of the wireless network (monitors, repeaters, network coordinator) can be based on the JN5168 microcontroller, which contains a 32-bit RISC processor with a clock frequency of 32 MHz and a wireless module for data transmission in accordance with the IEEE 802.15.4 standard. The ZigBee Pro stack was used to implement this network. The main

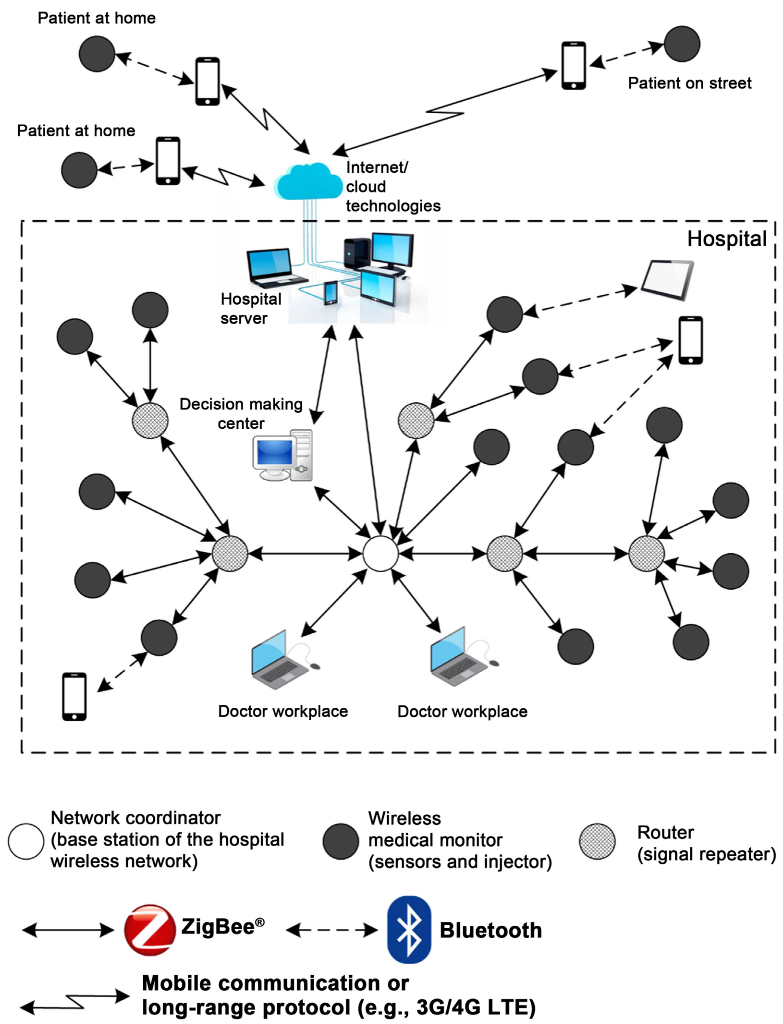

Figure 3. Smart remote medical monitoring system developed at V. M. Glushkov Institute of Cybernetics of the National Academy of Sciences.

control node of the wireless sensor network is the network coordinator node. In addition, the developed coordinator is designed to collect, pre-process, visualize and transfer data to a remote diagnostic centre for making the diagnosis. If necessary, the coordinator can provide communication with the Internet or a cloud environment. The workplace of a doctor in such a network is a personal computer with a ZigBee/USB adapter. If patients with wearable medical sensors are outside the clinic, it is advisable to supplement the ZigBee protocol with the Bluetooth 5.0 protocol. Bluetooth 5.0 protocol has high energy efficiency, which is especially important for battery-powered wearable data transmission. If the number of wearable medical sensors is large enough, the Bluetooth 5.0 protocol can deploy a Bluetooth Mesh network that can simultaneously support the health monitoring of many patients. To implement such a network, it is proposed to use a wireless microcontroller nRF52840 from Nordic Semiconductor, shown in Figure 4, which supports network operation under Bluetooth, Thread, ZigBee, 802.15.4, etc. protocols.

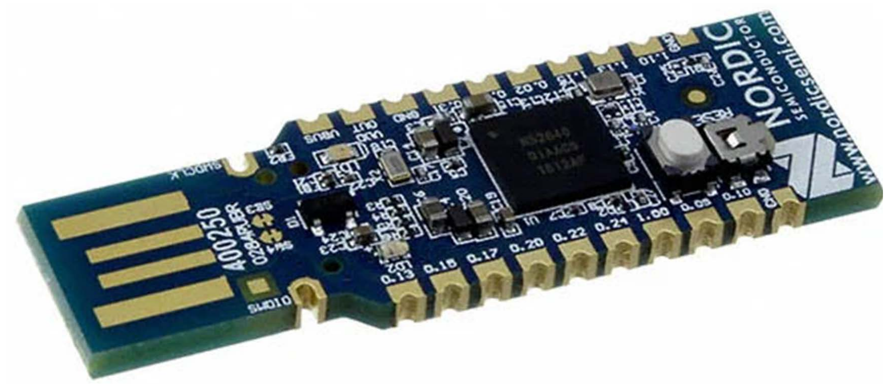

Figure 4. Wireless microcontroller nRF52840.

The microcontroller with a clock frequency of 64 MHz is based on a 32-bit processor with an ARM Cortex-M4 core. It includes SPI and QSPI interfaces, as well as a USB port and a built-in charger for the battery recharging. As follows from the above, due to the development of information technologies and microelectronic element base, remote smart medical monitoring systems are already the subject of engineering development and practical application [14]. It cannot be said about cognitive remote diagnostic centres using artificial intelligence. The decision is still up to the doctor. This means that tracking medical parameters using wearable medical sensors does not practically solve the problem of supporting the patient's condition at the required level, especially in emergency situations, when a delay in making a diagnosis, and therefore in providing timely medical care, can lead to death. Evaluation of the level of blood loss refers to such situations.

2.7. Calibration, Visualization, and Interpretation of the Individual Data of the Victim

With an increase in the number of medical parameters, transmitted to the diagnostic centre, the likelihood of an erroneous diagnosis also increases. In addition, there are still no international standards for medical monitoring hardware and software, which makes it difficult to ensure their compatibility in monitoring systems from different manufacturers. For these reasons, problems may arise both in the validity of data received by remote diagnostic centres and in the reliability of diagnosis based on these data. It is important to have personalized data under different physical and psychological stress for each possible victim. These data should be base lining calibration data obtained previously for each possible casualty. It should be noted that the statistical processing of a huge amount of data coming in real time to the computer diagnostic centre in case of injury or trauma, for example, a soldier, it is advisable to visualize them in the form of visual graphs, diagrams, or three-dimensional images [15] [16] with a mandatory interpretation in natural language, including recommendations to the medical staff. Critical situations can be represented as special markers reflecting a particular emergency. Considering the listed functions of a wearable monitoring system, for its effective use, it is advisable to use the Internet of Things (IoT) technology and elements of artificial intelligence (AI) to diagnose the severity of the condition to make a timely decision on the necessary assistance in real time.

3. Conclusions

1) The technology of the IoT, which is now widely used in medical practice, in our opinion, will be able to provide a solution to the problems of early detection of bleeding in combat conditions. Thanks to the introduction of IoT, sensor systems and wireless networks can become reliable assistants to doctors in the tasks of remote monitoring of the health of patients, including the wounded persons in combat conditions.

2) The presence of basic personalized information about the measured parameters is extremely important for early detection of bleeding in military (or other extreme) conditions.

3) An important problem of remote medical monitoring that needs to be solved is the use in such systems, along with smart sensors, of actuators (for example, remote injectors) under the control of AI. The solution to this problem is associated with the development and creation of new technology for use in healthcare—the technology of the Intelligent IoT or IIoT.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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