Acquisition and Transmission of ECG Signals Through Stainless Steel Yarn Embroidered in Shirts

Radu Adrian MUNTEANU[1], Sabin BANULEASA[1], Alexandru RUSU[2], Diana-Georgiana BUTACU[3]
[1]*Technical University of Cluj-Napoca, Cluj-Napoca, 400114, Romania*
[2]*Lexion Engineering SRL, Bucharest, Romania*
[3]*LockSys Expert SRL, Bucharest, Romania*
radu.a.munteanu@ethm.utcluj.ro

***Abstract*—A significant percent of all global deaths are caused by cardiovascular diseases (CVD). The diagnostic of the electrocardiogram (ECG) is a clinical practice widely adopted to evaluate the heart condition and identify CVD. For long-term ECG monitoring, a biopotential acquisition system integrated in common clothing is a viable solution for telemedicine. The electrodes and wires play a major role in the comfort and signal quality acquired from the patient. The paper presents a technical solution, where stainless steel yarn was used to create a Lead I Einthoven system consisting of 3 dry electrodes embroidered on a sports shirt. There are novel electrode materials and techniques that push further the state-of-the-art in ECG acquisition, but the authors focused on the currently available materials that are low-cost, widely available and easily integrable into common clothing, in order to seek a simple yet fully functional solution with the potential to become a truly ubiquitous ECG monitoring system.**

***Index Terms*—biomedical electrodes, biomedical telemetry, electrocardiography, telemedicine, wearable sensors.**

I. Introduction

Cardiovascular diseases (CVD) are the cause of 31% of all global deaths (17.9 million people), out of which 80% are from heart attacks and strokes, as reported by the World Health Organization [1]. This number is steadily increasing over the years and is becoming one of the major factors affecting human health.

The diagnostic of the electrocardiogram (ECG) is a clinical practice routinely used to evaluate the heart condition of the patient and has the potential to aid the identification of heart disease like myocardial injury, ischemia, the presence of prior infarction or disorders in the cardiac rhythm.

The clinical acquisition of the ECG is traditionally employed trough immobile (fixed) instruments or conventional portable Holter monitor systems designed for 24-48 hours of recording, but asymptomatic or intermittent properties of many chronic heart diseases require longer periods of ECG monitoring [2], and with a comfortable wear. Also, telemedicine is an emerging technology with potential of increasing efficiency and reducing costs in the medical field [3].

Conventional ECG systems acquire the bio-potential signal trough disposable gelled Ag/AgCl electrodes which provide a high-quality and stable signal. These electrodes are composed of a metallic snap fastener and reduce the impedance with the skin by using a solid or liquid hydrogel. In the case of long-term monitoring, they can cause discomfort and skin reactions [4]. Also, over time, the gel dries out and its performance degrades [5]. Adding on top of their discomfort, the electrodes are commonly coupled to the monitoring system via insulated wires routed under or over clothes.

Existing commercial solutions for a portable ECG acquisition and alert system have been developed to ensure increased ease of use and portability [6] and offer a higher degree of comfort and increased ECG signal quality during daily activities [7].

In terms of comfort for a long-term electronic monitoring system mounted on a patient, the system would be ideally fully integrated into common clothing. The major components that determine the comfort and signal quality of a long-term ECG system are the electrodes and the signal transmission to the central unit. Studies in the field and novelty papers indicate an increasing focus on innovative electrodes that offer high quality ECG signals in a variety of conditions and activities and reduced or no-skin contact for higher comfort.

In this paper, the authors present such a technical solution. Stainless steel yarn was chosen to be woven into a sports shirt. Several scenarios were determined for a subject, in order to collect ECG signals in diverse scenarios while comparing the results with the signal from conventional hydrogel Ag/AgCl electrodes with insulated wires. Since diagnostic of clinical ECG is typically realised by visual markers, we have determined a criteria of signal quality based on the PQRST complex, as illustrated in Fig. 1.

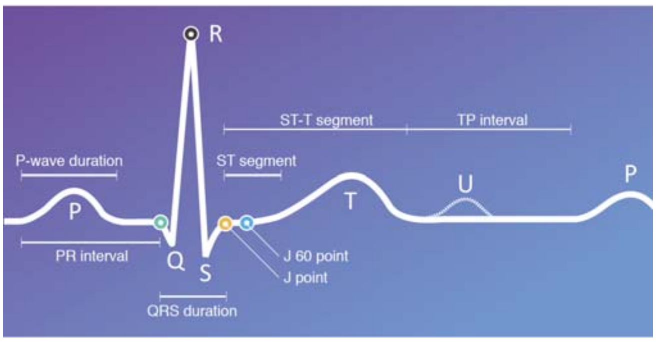

Figure 1. Schematic diagram of PQRST complex of the sinus rhythm of a human heart as seen on ECG [8]

Digital Object Identifier 10.4316/AECE.2020.02009

The obtained results indicate that dry electrodes wires made entirely from stainless steel are a feasible solution to a comfortable ECG acquisition system, especially in the presence of perspiration, which reduces the impedance of the skin-electrode contact.

There are novel electrode materials and techniques that push further the state-of-the-art in ECG acquisition, but the authors focused on the currently available materials that are low-cost, widely available and easy to integrate into common clothing, in order to seek a simple yet fully functional ECG monitoring system, with the potential to become truly ubiquitous.

II. Related Results in Literature

Electrodes are the interface between the signal acquisition system and the body bio-potential. They can be classified as polarizable or non-polarizable (dry versus wet electrodes) [9].

Non-polarizable electrodes have a current flow path between the electrode and the skin via a gel or other bio-signals conductive material (like electrodes from Ag/AgCl with hydrogel) [9].

Polarizable electrodes lack the current flow path and, instead, they work as a capacitive coupling between the conductive material and skin [9].

The polarizable electrodes can commonly be of two types: contact and non-contact.

Contact type electrodes, where the bio-potential conductive material is in direct connection with the skin, includes various types of electrode materials, such as: stainless steel yarn [9-12], stainless steel surfaces [13], polyamide wires coated with stainless steel [14], Ag fibres [10],[15-16], Ag textiles [17-18], Ag coated polyimide [19-20], Ag plated PVDF [21] or polyamide [22], Ag nanowire [23], Ag coated glass composite [24], Ag coated Nylon [25], Ag printing [26-27] or other materials like Ni and Cu on fibers or textiles [11], [16], [25]. A novelty is the use of carbon-based electrodes (nanotubes, nanofibers, graphite or particles) [28-32], that have great potential to reduce motion artefacts and adapt to special conditions [26], [33]. Easy printing using commercially available equipment of PEDOT: PSS poly (3,4-ethylenedioxythiophene) organic polymer has led to the development of novel electrodes for ECG signal acquisition [34-37] which, although they may share some of the disadvantages of motion artefacts because of their dry nature, the leads can be made up of a high number of printed electrodes in common clothing in order to post-filter out more easily the influence factors.

Non-contact type electrodes are also known as capacitive coupling electrodes, where there is material in-between the electrode conductive plate and the skin, typically textile material like cotton or polyester [38-43]. These types of electrodes promise the best comfort by truly integrating the electrodes into clothing, ideally with no-skin contact, but typically they have a lower ECG signal quality than those with direct contact and can suffer from motion artefacts.

Visual diagnosis of clinical ECG by specialized medical staff is a widely accepted procedure for evaluating the heart condition or identifying CVD. Also, a typical approach to the digital characterization of the analogue ECG signal is by adopting the Heart Rate Variability (HRV) metrics and norms that describe 24h, short-term (~5 min) or brief, and ultra-short-term (<5 min) intervals using time-domain, frequency-domain, and non-linear measurements [44-45].

One main challenge to create a truly ubiquitous ECG system is to be low-cost, which can be achieved not only trough raw material cost reduction, but also by considering the current manufacturing processes which typically involve a logistics chain from clothing producers to electronics integrators. That is why we believe it is important to identify ways such that electrodes, wires and digital processing units can be manufactured or easily integrated directly by clothing producers. Following the logic of widely available and low-cost materials, this is one of the reasons why the authors have chosen to study the feasibility of ECG signal acquisition via stainless steel yarn woven and embroidered into a sports shirt.

III. Proposed ECG System

A. Overview

The proposed ECG acquisition system consists of a single lead made of 3 dry electrodes in accordance with the L1 lead of Einthoven's triangle. The placements chosen were right and left upper arm and right abdomen. The upper arm positions offer an advantageous stretch of the shirt to increase pressure on the electrode-skin contact, in order to reduce impedance. All 3 dry electrodes are connected, using the same stainless-steel yarn, to the AD8232 module. Fig. 2 shows the system embroidered into a sports T-shirt (polyester 82% and 18% elastane).

B. Dry electrodes

The embroidered dry electrodes chosen pattern was from a previous study [15] where it had the best performance as a "Finnesd"-type silver fiber. The electrodes were made by weaving stainless steel yarn onto a piece of cotton textile which later was embroidered on the inside of the sports shirt in the locations shown in Fig. 2.

C. Transmission wires

The transmission wires are routed on the exterior surface of the shirt with no direct skin contact, in a zig-zag line, to prevent stretching of the wire, which can modify its resistivity or even break it.

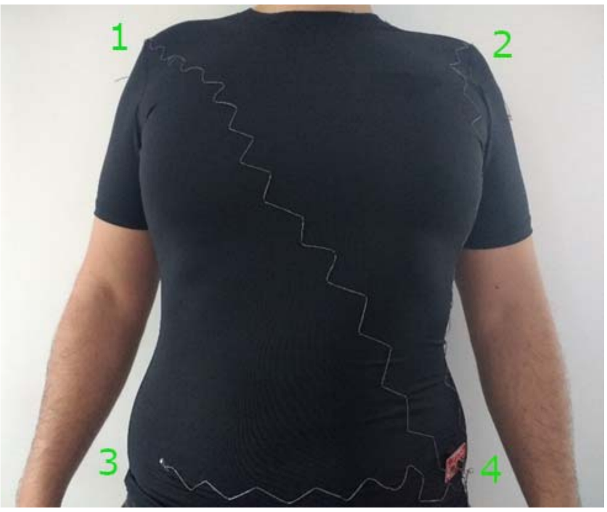

Figure 2. Dry electrode pads and transmission wires made from stainless steel thread and embroided into a strech T-shirt (1) right electrodes (2) left electrode (3) right leg electrode (4) AD8232 module

D. ECG signal processing

The AD8232 module is designed to work with a single lead 3-electrode configuration which outputs the filtered and amplified ECG signal to be measured by an oscilloscope from Picoscope series 2000. The presented ECG signals represent the raw output of the AD8232 module with no post-filtering or amplification.

E. Proposed tests

The following tests were realised sequentially, with the precedent test conditions being used for the next test with small modifications, in order to identify which variables account as the most negative influence factors.

Test 1:

A reference ECG signal was acquired to be later used for comparison, using conventional Ag/AgCl hydrogel electrodes connected with PVC insulated copper wires with the AD8232 module, to record the reference signal, placed in the exact same locations as the dry electrodes shown in Figure 2. The shirt was worn in a comfortable, natural manner and the subject was sitting straight at ease.

Test 2:

The copper wires were replaced with woven stainless-steel yarn on to the exterior of the shirt, in order to connect the snap fasteners of the gelled electrodes to the AD8232 module.

Test 3:

The hydrogel Ag/AgCl electrodes were replaced with the dry woven stainless-steel yarn electrodes embroidered on the inside of the shirt, as shown in Figure 3. The dry electrodes were placed on the right and left upper arms, as in Figure 2, and connected with the existing stainless-steel woven yarn used as ECG signal transmission wires to the AD8232 module.

Test 4:

A slight pressure on the electrodes on the right and left upper arms, in order to increase the electrode-skin contact and decrease impedance, was applied using a 3N force on the left and right electrodes.

Test 5:

The 3 electrodes were wetted to simulate natural perspiration during intense activities, using a solution of salty water containing 1% NaCl. As literature indicates, this greatly reduces the contact impedance between the electrode and the skin and reduces greatly the motion artefacts that deter the ECG signal acquisition during physical activities.

Test 6:

The subject lies down on its back in resting position.

Test 7:

The subject doing squats. The electrodes were still wet with salty water.

Test 8:

The subject doing a cool-off after the squats exercise.

F. Results evaluation

This study used as a basis for signal quality the visual evaluation of the ECG by analysis of the P, QRS and T waves, the PR and QRS interval duration and regularities of the QRS complexes [46]. The signal quality was classified into 4 types, in comparison with the results from Test 1 used as a fiducial signal, see Table 1.

TABLE I. ECG RAW SIGNAL VISUAL EVALUATION CRITERIA

Result	Visual evaluation method
Excellent	Signal is indistinguishable from the reference from Test 1
Good	PQRST points are easily identifiable as in Fig.1
Poor	Noise and artefacts make it difficult to identify waves and segments, excluding the R peaks
Unidentifiable	Cannot identify R peaks

Secondly, we have used the HRV time-domain measurements to quantify the indices mean RR interval, standard deviation of all RR intervals (SDNN), square root of the mean of the sum of the squares of differences between adjacent RR intervals (RMSSD) and the number of pairs of adjacent RR intervals differing by more than 50ms in the entire recording (NN50 count) [32], [46-47] from the acquired ECG signals.

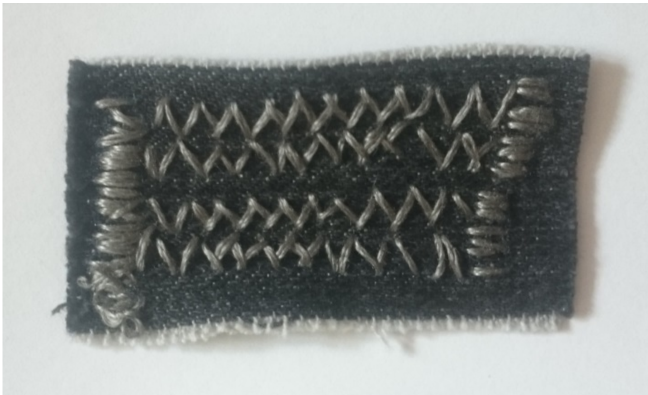

Figure 3. A dry electrode made from stainless steel yarn woven into cotton textile

IV. RESULTS AND DISCUSSIONS

Test 1:

Fig. 4 shows the resulting ECG signal from conventional Ag/AgCl with hydrogel adhesive and insulated copper wires. Movement artefacts caused minimal noise during testing, such that the PQRST complex was, at all times, clearly distinguishable.

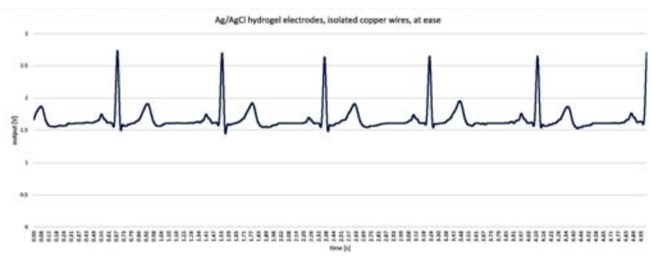

Figure 4. Ag/AgCl hydrogel commercial electrodes, insulated copper wires, raw voltage output of the AD8232 module in a 5 seconds frame, subject sitting at ease

Test 2:

The insulated copper wires were replaced with the woven stainless-steel yarn on top of the shirt. Fig. 5 shows the ECG signal in this scenario. There was no impact on the comfort, as the wires were routed on the exterior of the shirt. The results were nearly identical to the first test. The wires proved to be a very good carrier for the ECG signal.

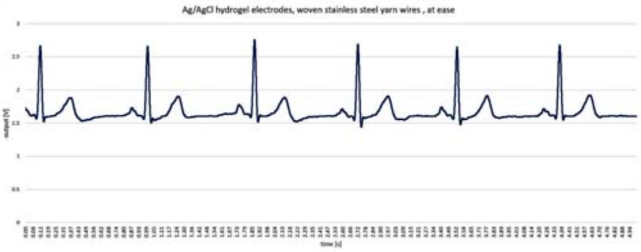

Figure 5. Ag/AgCl hydrogel commercial electrodes, stainless steel yarn as transmission wires, raw voltage output of the AD8232 module in a 5 seconds frame, subject sitting at ease

Test 3:

The dry electrodes have no adherence with the skin and, therefore, generate motion artefacts in the ECG signal. The results were very much influenced by the movement of the subject, by the pressure applied on the electrodes and by the wetness of the electrodes, as already identified in tests of several other papers [25], [36], [46], [48-52].

The majority of the 1-minute ECG recording resulted in a poor signal where only the R peaks were distinguishable and only when the subject was completely still. The ECG signal was poor, as shown in Fig. 6.

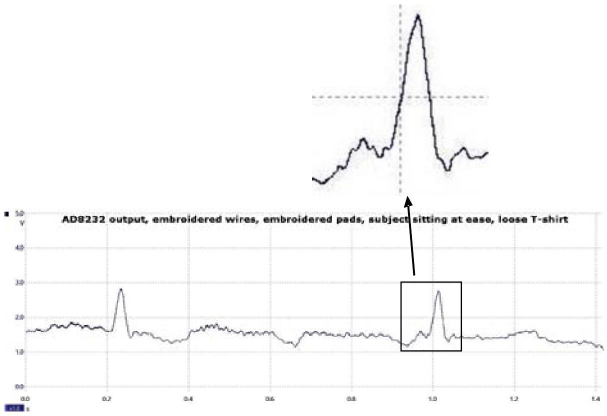

Figure 6. Dry electrodes, stainless steel yarn as transmission wires. raw voltage output of the AD8232, subject sitting at ease

Test 4:

Pressure upon the two upper electrodes increased signal quality from poor to good, while the subject was sitting at ease, as shown in Fig. 7.

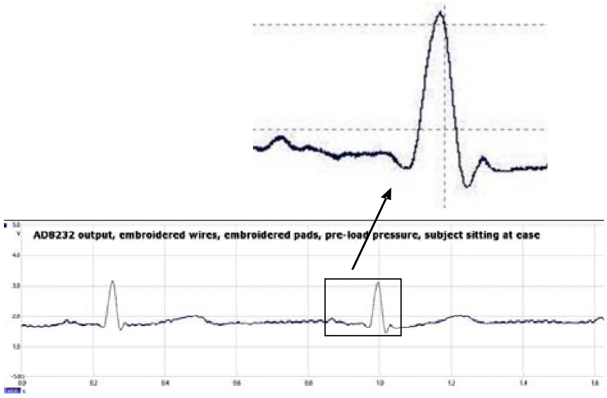

Figure 7. Dry electrodes, stainless steel yarn as transmission wires, pressure applied on the top electrodes, raw voltage output of the AD8232 module in a 4 seconds frame, subject sitting at ease

Test 5:

Applying wetness to the electrodes - with salty water, a good electrical conductor, - greatly increased the ECG signal quality to excellent, as shown in Fig. 8.

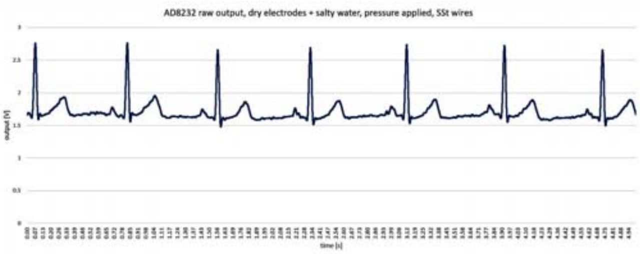

Figure 8. Dry electrodes, stainless steel yarn as transmission wires, pressure applied on the top electrodes, salty water added on all 3 electrodes, raw voltage output of the AD8232 module in a 5 seconds frame, subject sitting at ease

Test 6:

Subject lying down. We observed a more stable signal, with less noise, Fig. 9.

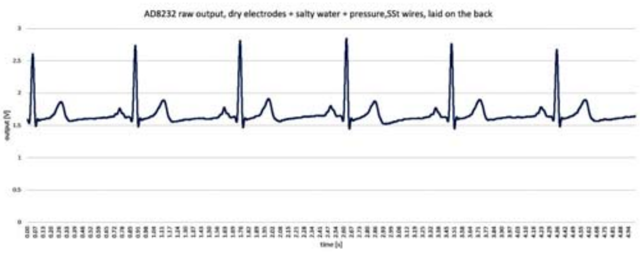

Figure 9. Dry electrodes, stainless steel yarn as transmission wires, pressure applied on the top electrodes, salty water added on all 3 electrodes, raw voltage output of the AD8232 module in a 5 seconds frame, subject sitting laid down on its back

Test 7:

Subject doing an intense physical activity - squats. The resulting ECG signal is poor, as even though it presents clear R peaks but lacks the clear visual identification of the P and T waves. Given the location chosen for the electrodes, ECG interferences were not significant enough to distort the signal, Fig. 10.

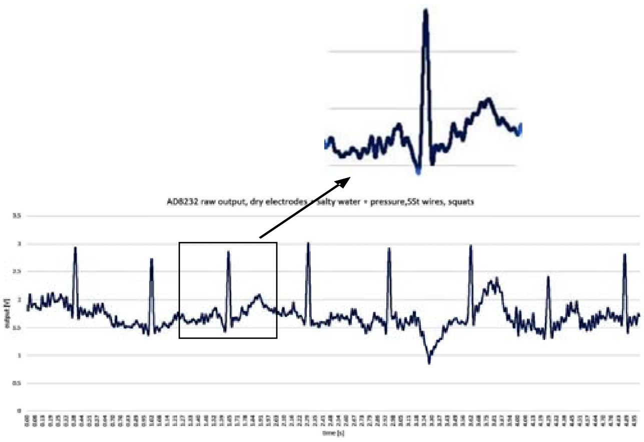

Figure 10. Dry electrodes, stainless steel yarn as transmission wires, pressure applied on the top electrodes, salty water added on all 3 electrodes, raw voltage output of the AD8232 module in a 5 seconds frame, subject doing squats

Test 8:

Subject ECG signal acquisition during cool off, after doing squats, shows a better-quality signal than the one in the previous test and has some PQRST complexes that can be classified as good quality signal, allowing for short-term HRV analysis, Fig.11.

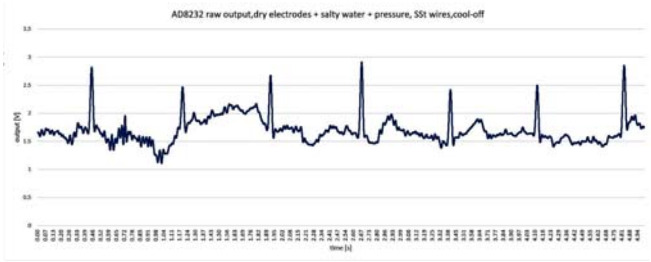

Figure 11. Dry electrodes, stainless steel yarn as transmission wires, pressure applied on the top electrodes, salty water added on all 3 electrodes, raw voltage output of the AD8232 module in a 5 seconds frame, subject during cool-off after squats

Table II shows the results of all the above tests.

TABLE II. TESTS RESULTS

Test	Result	Observation
1	-	Conventional ECG system
2	Excellent	Stainless steel wires capable of carrying ECG signal on top of the shirt
3	Poor	Dry stainless-steel electrodes had poor performance
4	Good	Pressure on the electrodes improved performance
5	Excellent	Salty water was a great contact impedance reducer
6	Excellent	Short moments of rest by the patient could capture excellent ECG signal
7	Poor	ECG acquisition of poor quality during exercise was possible
8	Good	Short-term HRV during motion is possible

V. CONCLUSION

The problem of acquiring the ECG signal with the help of textile or woven electrodes is of great interest and topicality. The paper studies the feasibility of the acquisition and transmission of ECG signals trough stainless steel yarn electrodes embroidered into common clothing and transmitted through stainless steel wires, without the use of gels for electrodes (a solution that could be useful in monitoring people at home). The authors have focused on the currently available materials that are low-cost, widely available and easy to integrate into common clothing, in order to seek a simple yet fully functional ECG monitoring system. The cardiologist uses the ECG signal for surveillance, signal which can be transmitted over the Internet. In addition, the physician realizes if something is abnormal with the heart rate even only from the examination of the R wave, which can be well seen also in poor quality signals. Following the above tests, we are encouraged to conclude that the system could provide a substantial amount of useful information about the subject's heart condition, in order to become a telemedicine clinically approved solution. Even if good and excellent results are obtained for static positions of the subject, we easily observe that perspiration plays a very important role in the electrode-skin impedance, which translates directly to increased ECG signal quality, making it suitable for future tests for monitoring people who are exercising or are professional athletes, with the potential to become truly ubiquitous. As a follow-up, we can try to parameterize the ECG signal and, together with the cardiologist, develop a numerical evaluation method.

REFERENCES

[1] https://www.who.int/cardiovascular_diseases/world-heart-day/en/

[2] D. Jabaudon, J. Sztajzel, K. Sievert, T. Landis, R. Sztajzel, "Usefulness of ambulatory 7-day ECG monitoring for the detection of atrial fibrillation and flutter after acute stroke and transient ischemic attack," in Stroke, J. Amer. Heart Assoc., vol. 35, pp. 1647–1651, May 2004. doi:10.1161/01.STR.0000131269.69502.d9

[3] I. Ungurean, A. Brezulianu, " An Internet of Things Framework for Remote Monitoring of the HealthCare Parameters," Advances in Electrical and Computer Engineering, vol. 17, no. 2, pp. 11–16, 2017. doi:10.4316/AECE.2017.02002

[4] J. Crawford, L. Doherty, "Practical aspects of ECG recording", M&K Update Ltd, UK, pp. 44, 2012.

[5] A. Searle, L. Kirkup, "A direct comparison of wet, dry and insulating bioelectric recording electrodes," Physiol. Meas., vol. 21, pp. 271–283, 2000. doi:10.1088/0967-3334/21/2/307

[6] https://www.getqardio.com/qardiocore-wearable-ecg-ekg-monitor-iphone/, "QardioCore – WEARABLE ECG/EKG", Qardio Inc., 2019

[7] https://www.alivecor.com/, "KardiaMobile - Take a medical-grade EKG anytime, anywhere", AliveCor Inc., 2019

[8] A. Rawshani, "Pocket guide to ECG interpretation", University of Gothenburg, pp. 1, 2017

[9] B. Taji, S. Shirmohammadi, V. Groza and I. Batkin, "Impact of skin–electrode interface on electrocardiogram measurements using conductive textile electrodes," in IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 6, pp. 1412-1422, June 2014. doi:10.1109/TIM.2013.2289072

[10] H. Carvalho, A. P. Catarino, A. Rocha and O. Postolache, "Health monitoring using textile sensors and electrodes: An overview and integration of technologies," 2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Lisboa, 2014, pp. 1-6. doi:10.1109/MeMeA.2014.6860033

[11] G. Cho, K. Jeong, M. J. Paik, Y. Kwun and M. Sung, "Performance evaluation of textile-based electrodes and motion sensors for smart clothing," in IEEE Sensors Journal, vol. 11, no. 12, pp. 3183-3193, Dec. 2011. doi:10.1109/JSEN.2011.2167508

[12] M. A. Mestrovic, R. J. N. Helmer, L. Kyratzis and D. Kumar, "Preliminary study of dry knitted fabric electrodes for physiological monitoring," 2007 3rd International Conference on Intelligent Sensors, Sensor Networks and Information, Melbourne, Qld., 2007, pp. 601-606. doi:10.1109/ISSNIP.2007.4496911

[13] V. Randazzo, E. Pasero and S. Navaretti, "VITAL-ECG: A portable wearable hospital," 2018 IEEE Sensors Applications Symposium (SAS), Seoul, 2018, pp. 1-6. doi:10.1109/SAS.2018.8336776

[14] M. Hanic et al., "BIO-monitoring system with conductive textile electrodes integrated into t-shirt," 2014 24th International Conference Radioelektronika, Bratislava, 2014, pp. 1-4. doi:10.1109/Radioelek.2014.6828472

[15] T. Pola and J. Vanhala, "Textile electrodes in ECG measurement," 2007 3rd International Conference on Intelligent Sensors, Sensor Networks and Information, Melbourne, Qld., 2007, pp. 635-639. doi:10.1109/ISSNIP.2007.4496917

[16] M. Uzun, E. Sancak and I. Usta, "The use of conductive wires for smart and protective textiles," 2015 E-Health and Bioengineering Conference (EHB), Iasi, 2015, pp. 1-4. doi:10.1109/EHB.2015.7391494

[17] M. G. Srinivasa, P. S. Pandian, "Dry electrodes for bio-potential measurement in wearable systems," 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), Bangalore, 2017, pp. 270-276. doi:10.1109/RTEICT.2017.8256600

[18] R. Ambrosio, C. Guevara, C. Silva, A. Heredia, M. Moreno, "Electrical characterization of textile electrodes for an ECG acquisition system," 11th International Conference on Electrical Engineering, Computing Science and Automatic Control, Campeche, Mexico, 2014, pp. 1-6. doi:10.1109/ICEEE.2014.6978306

[19] Y. A. Bhagat, P. Vcrdon, S. Avuthu, D. Parsons, M. Sussman, G. Wable, R. Hugeneck, "Like Kleenex for Wearables: A soft, strong and disposable ECG monitoring system," IEEE Biomedical Circuits and Systems Conference (BioCAS), Cleveland, OH, 2018, pp. 1-1. doi:10.1109/BIOCAS.2018.8584778

[20] T. Apiwattanadej, L. Zhang, H. Li, "Electrospun polyurethane microfiber membrane on conductive textile for water-supported textile electrode in continuous ECG monitoring application," Symposium on Design, Test, Integration & Packaging of MEMS and MOEMS, Roma, 2018, pp. 1-5. doi:10.1109/DTIP.2018.8394190

[21] T. I. Oh, S. Yoon, T. E. Kim, H. Wi, K. J. Kim, E. J. Woo, R. Sadleir, "Nanofiber web textile dry electrodes for long-term biopotential recording," IEEE Transactions on Biomedical Circuits and Systems,

vol. 7, no. 2, pp. 204-211, April 2013. doi:10.1109/TBCAS.2012.2201154

[22] T. Pereira, H. Carvalho, A. P. Catarino, M. J. Dias, O. Postolache, P. S. Girão, "Wearable biopotential measurement using the TI ADS1198 analog front-end and textile electrodes," IEEE International Symposium on Medical Measurements and Applications, Gatineau, QC, 2013, pp. 325-330. doi:10.1109/MeMeA.2013.6549761

[23] A. C. Myers, H. 1 Huang, Y. Zhu, "Wearable silver nanowire dry electrodes for electrophysiological sensing," RSC Adv., vol. 5, no. 15, pp.11627–11632, 2015. doi:10.1039/C4RA15101A

[24] P. Sarati Das, J.-Y. Park, "A flexible touch sensor based on conductive elastomer for biopotential monitoring applications," Biomedical Signal Processing and Control, vol. 33, pp. 72–82, Nov. 2017. doi:10.1016/j.bspc.2016.11.008

[25] M. A. Mestrovic, R. J. N. Helmer, L. Kyratzis, D. Kumar, "Preliminary study of dry knitted fabric electrodes for physiological monitoring," 3rd International Conference on Intelligent Sensors, Sensor Networks and Information, Melbourne, Qld., 2007, pp. 601-606. doi:10.1109/ISSNIP.2007.4496911

[26] M. Inoue, Y. Amano, Y. Tada, "Design of printed E-textile probers to supress electrocardiogrpay noise," International Conference on Electronics Packaging (ICEP), Yamagata, 2017, pp. 464-465. doi:10.23919/ICEP.2017.7939421

[27] T. Takeshita, M. Yosihda, A. Ouchi, A. Hinoki, H. Uchida, T. Kobayashi, "Development of multi-lead ECG measurement wear using electrostatic flocking technology," International Conference on Electronics Packaging and iMAPS All Asia Conference (ICEP-IAAC), Mie, 2018, pp. 145-146. doi:10.23919/ICEP.2018.8374690

[28] Y. S. Noh, J. Bales, R. Bersain, J. Molignano, A. Clement, D. Pins, J. Florian, K. Chon, "Novel conductive carbon black and polydimethlysiloxane ECG electrode: a comparison with commercial electrodes in fresh, chlorinated, and salt water," Ann. Biomed. Eng., vol. 44, no. 8, pp.2464–2479, 2016. doi:10.1007/s10439-015-1528-8

[29] H. Jung, "Carbon based electrode for wearable biosignal monitoring patch," 2018 International Flexible Electronics Technology Conference (IFETC), Ottawa, ON, 2018, pp. 1-2. doi:10.1109/IFETC.2018.8583893

[30] H. Jung, J. Moon, D. Baek, J. Lee, Y. Choi, J. Hong, S. Lee, "CNT/PDMS Composite flexible dry electrodesfor long-term ECG monitoring," IEEE Transactions on Biomedical Engineering, vol. 59, no. 5, pp. 1472-1479, May 2012. doi:10.1109/TBME.2012.2190288

[31] Y.S. Noh, X. Ye, L. Murphy, C. Eaton-Robb, T. Dimitrov, W. J. Choi, K. Chon, "Increased conductivity and reduced settling time of carbon-based electrodes by addition of sea salt for wearable application," 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, HI, 2018, pp. 1291-1294. doi:10.1109/EMBC.2018.8512510

[32] T. Thap, K.-H. Yoon, J. Lee, "Graphite based electrode for ECG monitoring: evaluation under freshwater and saltwater conditions," Sensors, vol. 16, no. 4, p. 542, Apr. 2016. doi:10.3390/s16040542

[33] B. A. Reyes, H. Posada-Quintero, J. Bales, A. Clement, G. Pins, A. Swiston, J. Riistama, J. Florian, B. Shykoff, M. Qin, K. Chon, "Novel electrodes for underwater ECG monitoring," IEEE Trans. Biomed. Eng., vol. 61, no. 6, pp. 1863–1876, Jun. 2014. doi:10.1109/TBME.2014.2309293

[34] A. Achilli, D. Pani, A. Bonfiglio, "Characterization of screen-printed textile electrodes based on conductive polymer for ECG acquisition," Computing in Cardiology (CinC), Rennes, 2017, pp. 1-4. doi:10.22489/CinC.2017.129-422

[35] D. Pani, A. Dessì, J. F. Saenz-Cogollo, G. Barabino, B. Fraboni, A. Bonfiglio, "Fully textile, PEDOT:PSS based electrodes for wearable ECG monitoring systems," in IEEE Transactions on Biomedical Engineering, vol. 63, no. 3, pp. 540-549, March 2016. doi:10.1109/TBME.2015.2465936

[36] C. Wang, Y. Qin, H. Jin, I. Kim, J. Granados, C. Dong, Y. Jiang, Q. Zhou, J. Li, Z. He, Z. Zou, L. Zheng, X. Wu, Y. Wang, "A low power cardiovascular healthcare system with cross-layer optimization from sensing patch to cloud platform," IEEE Transactions on Biomedical Circuits and Systems, January 2019. doi:10.1109/TBCAS.2019.2892334

[37] C. Srichan, T. Saikrajang, T. Lomas, A. Jomphoak, T. Maturos, D. Phokaratkul, T. Kerdcharoen, A. Tuantranont, "Inkjet printing PEDOT:PSS using desktop inkjet printer," 6th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Pattaya, Chonburi, 2009, pp. 465-468. doi:10.1109/ECTICON.2009.5137049

[38] A. V. Guatapi G., C. A. Carabali C., A. R. Robin, "Development of a low cost mobile system for monitoring cardiac activity based on noncontact electrodes," 2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM), Cuenca, 2018, pp. 1-6. doi:10.1109/ETCM.2018.8580304

[39] S. Majumder, L. Chen, O. Marinov, C. Chen, T. Mondal, M. J. Deen, "Noncontact wearable wireless ECG Systems for long-term monitoring," IEEE Reviews in Biomedical Engineering, vol. 11, pp. 306-321, 2018. doi:10.1109/RBME.2018.2840336

[40] M. Chen, I. Dario Castro, Q. Lin, T. Torfs, F. Tavernier, C. Van Hoof, N. Van Helleputte, Nick. "A 400GΩ input-impedance, 220MVpp linear-input-range, 2.8Vpp CM-interference-tolerant active electrode for non-contact capacitively coupled ECG acquisition," VLSI Circuits, pp. 129-130, 2018. doi:10.1109/VLSIC.2018.8502270

[41] S. Fuhrhop, S. Lamparth, S. Heuer, "A textile integrated long-term ECG monitor with capacitively coupled electrodes," IEEE Biomedical Circuits and Systems Conference, Beijing, 2009, pp. 21-24. doi:10.1109/BIOCAS.2009.5372095

[42] E. Nemati, M. J. Deen, T. Mondal, "A wireless wearable ECG sensor for long-term applications," IEEE Communications Magazine, vol. 50, no. 1, pp. 36-43, January 2012. doi:10.1109/MCOM.2012.6122530

[43] Y. G. Lim, K. K. Kim, K. S. Park, "ECG recording on a bed during sleep without direct skin-contact," IEEE Transactions on Biomedical Engineering, vol. 54, no. 4, pp. 718-725, April 2007. doi:10.1109/TBME.2006.889194

[44] A. N. Londhe, M. Atulkar, "Heart rate variability analysis: application overview," Second International Conference on Inventive Communication and Computational Technologies (ICICCT), India, 2018, pp. 1518-1523. doi:10.1109/ICICCT.2018.8473198

[45] F. Shaffer, J. P. Ginsberg, "An overview of heart rate variability metrics and norms," Frontiers in Public Health, vol. 5, pp. 1–17, September 2017. doi:10.3389/fpubh.2017.00258

[46] M. Paralič, R. Hudec, "The application development for measuring and evaluating ECG data for home health care using smart clothes," New Trends in Signal Processing (NTSP), Demanovska Dolina, 2018, pp. 1-5. doi:10.23919/NTSP.2018.8524104

[47] R. Aoki, K. Eguchi, S. Shimauchi, K. Yoshida, T. Yamada, "Consideration of calculation process assuming heart rate variability analysis using wearable ECG devices," 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Honolulu, HI, 2018, pp. 5693-5696. doi:10.1109/EMBC.2018.8513449

[48] A. Catarino, H Carvalho, M. Dias, T. Pereira, O. Postolache, P. Silva Girao, "Continuous health monitoring using E-textile integrated biosensors," International Conference and Exposition on Electrical and Power Engineering, Iași, 2012, pp. 605-609. doi:10.1109/ICEPE.2012.6463867

[49] A. Achilli, A. Bonfiglio, D. Pani, "Design and characterization of screen-printed textile electrodes for ECG monitoring," in IEEE Sensors Journal, vol. 18, no. 10, pp. 4097-4107, May 2018. doi:10.1109/JSEN.2018.2819202

[50] S. Kim, S. Leonhardt, N. Zimmermann, P. Kranen, D. Kensche, E. Muller, C. Quix, "Influence of contact pressure and moisture on the signal quality of a newly developed textile ECG sensor shirt," 5th International Summer School and Symposium on Medical Devices and Biosensors, Hong Kong, 2008, pp. 256-259. doi:10.1109/ISSMDBS.2008.4575068

[51] B. Taji, S. Shirmohammadi, V. Groza, "Measuring skin-electrode impedance variation of conductive textile electrodes under pressure," IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, Montevideo, 2014, pp. 1083-1088. doi:10.1109/I2MTC.2014.6860909

[52] M. McKnight, T. Agcayazi, H. Kausche, T. Ghosh, A. Bozkurt, "Sensing textile seam-line for wearable multimodal physiological monitoring," 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Orlando, FL, 2016, pp. 311-314. doi:10.1109/EMBC.2016.7590702