The Impact of ECG Sensor Design on Signal Noise

Marie Riis Dammeyer, MSc., R&D Engineer & Daniel Hansen, PhD, R&D Engineer
August 2021, Ambu A/S

Introduction

Electrocardiogram (ECG) sensors are used for detecting biopotentials generated by the heart. The biopotential propagates from the heart through ions in the body's physiological liquid and can be detected by a pair of ECG sensors attached to the skin. This provides healthcare professionals with spatial electrical and physiological information of the heart depending on the position of the ECG sensors. Such sensors typically include an electrolyte gel to reduce the electrical impedance of the skin and detect the biopotential, a silver/silver chloride (Ag/AgCl) electrode to electro-chemically convert the ECG signal from ion polarization to electricity and a skin adhesive to attach the sensor securely to the skin [1-5]. To ensure high quality of the acquired ECG signal, each sensor component must be carefully optimized and tailored for specific clinical procedures such as Holter monitoring, 12-lead ECG, or stress tests. When worn, the ECG sensors may be subjected to external forces such as friction from clothes, lead wire pulling, and external push forces. These external forces may displace the sensor or alter the electrical contact area between the sensor and skin (sensor area), which will cause artifacts in the ECG signal or completely compromise the signal. The sensor construction, geometry and materials influence the effect of external mechanical forces. Consequently, the ECG sensor must be designed to minimize the influence of mechanical stimuli during wear by dissipating forces away from the sensor area. Furthermore, the ECG sensor design influences how the user and patient interact with the sensor during application and wear.
In this paper, two ECG sensor design concepts are described and then evaluated in terms of ease of use and ability to mitigate motion artifacts originating from external mechanical forces.

Center Fitting ECG Sensor Design

ECG sensors with a center fitting design are typically constructed with axial symmetry where the electrical components of the device are stacked as shown in Figure 1. The electrical components include an electrolyte gel, an Ag/AgCl electrode, a fitting, and a lead wire to transmit the electrical signal (Figure 1a). The electrical components are surrounded by a skin adhesive, which primary function is to ensure that the sensor is securely attached to the skin for the desired duration of use. The assembled ECG sensor (Figure 2b) can readily be attached to the skin and used in pairs for various ECG recordings.

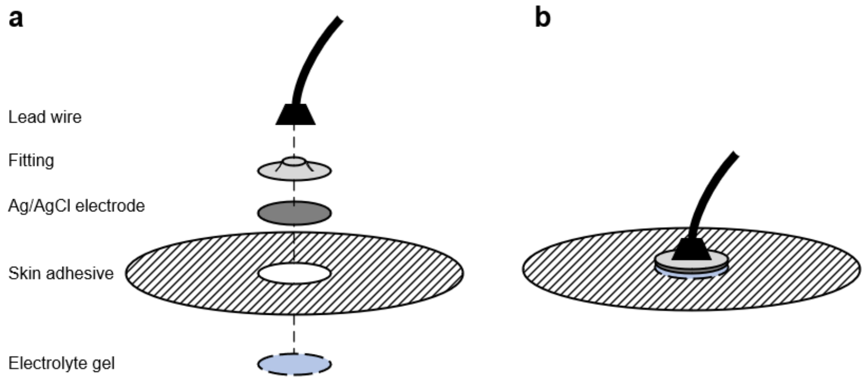

***Figure 1**: Schematic illustration of an ECG sensor with center fitting design in exploded view (a) and assembled (b).*

Offset Fitting ECG Sensor Design

The offset fitting design represents an alternative design to the center fitting design. Here, the electrolyte gel and Ag/AgCl electrode are also surrounded by the skin adhesive. However, from the Ag/AgCl electrode, the signal is transmitted away from the sensor area by a conductor (Figure 2a) to allow the fitting to be displaced from the sensor area of the ECG sensor [6]. In between the conductor and fitting, a material layer, referred to as the offset element, is placed to insulate the conductor and provide mechanical stability. The offset element is anchored to the backside of the skin adhesive around the sensor area, which is represented by the dashed circle in Figure 2b. The offset element also allows the fitting to bend (Figure 2b), which yields higher degree of flexibility during use. During flexing, the conductor follows the offset element, which provides mechanical integrity and prevents kinks to the conductor, which could disturb the signal. In the following section, the offset fitting design will be compared with the center fitting design in terms of their ability to mitigate signal noise when exposed to external mechanical disturbances in clinical settings.

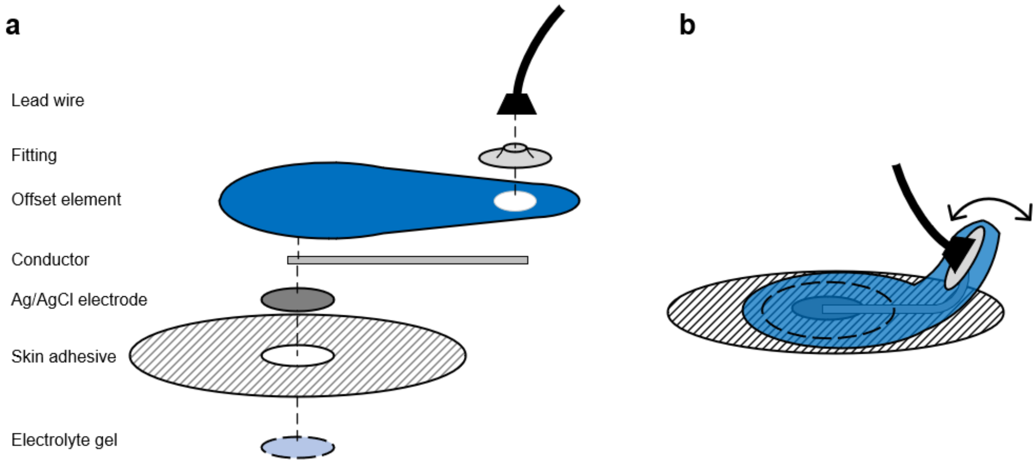

Figure 2: *Schematic illustration of the offset fitting design in exploded view (a) and as an assembled sensor (b). The design includes the offset element, which is anchored to the backside of the skin adhesive indicated by the dashed circle (b).*

Signal Noise, Motion Artifacts & False Alarms

ECG sensors are widely used for patient monitoring in combination with other vital sign sensors for overall assessment of the condition of the patient. In environments such as the cardiac care unit and the intensive care unit, ECG signals of patients are continuously monitored and evaluated. In case of life-threatening cardiac arrythmias, the health care professionals are alerted. Although alarms are necessary for timely medical aid in critical situations, so-called false alarms also occur without clinical relevance due to motion artifacts, electromagnetic noise, and sensor detachment [7, 8]. False alarms have been reported to represent more than 80 % of all alarms and may lead to increased stress and wasted time for the healthcare professionals, while patients may experience reduced quality of sleep, stress, and depressed immune response [9, 10]. Furthermore, excessive false alarms cause alarm fatigue and reduced alarm response rate of the health care professionals, which ultimately is life-threatening for the patients [11]. It is challenging to decouple different contributions to noise and artifacts in ECG signals leading to alarms in clinical settings, however, it is certain that the electrical contact between the sensor and skin intrinsically influence the quality of the obtained signal. Several circumstances will affect the effective sensor area during sensor application and wear depending on the ECG sensor design. Here, two general situations are considered: External pressure on the sensor and pulling on the lead wire during wear.

External Pressure on the ECG Sensor

ECG sensors are exposed to external pressure during connection of the lead wire and if the patient lies on the sensor. Pressure on the sensor area may compromise the structural integrity of the gel, which leads to the gel spreading at the skin—adhesive interface. Spreading of the gel alters the effective sensor area, which causes changes in the obtained ECG signal and potentially set off alarms. Furthermore, it reduces the sensor's adhesion to the skin, which may lead to untimely sensor detachment. For most ECG sensors, the bulkiest part of the sensor is the fitting and lead wire connector. The fitting is therefore most likely to be subjected to external pressure during wear and lead wire application. Figure 3 illustrates the connection of the lead wire for center fitting (Figure 3a) and offset fitting (Figure 3b) ECG sensors. For the ECG sensor with the center fitting design, the force required to connect the lead wire is applied to the sensor area, which causes the gel to spread at the skin—adhesive interface (Figure 3a). Unlike sensors with center fitting, the offset fitting design allows the user to connect the lead wire without applying excessive force to the sensor area, which prevents gel spreading at the skin—adhesive interface (Figure 3b). The offset design also allows the user to support the backside of the fitting, while connecting the lead wire, which enables connection of the lead wire without applying any pressure to the patient. In situations such as showering or transport, it is convenient to disconnect and reconnect the ECG sensors from the signal acquisition device. Here, the offset fitting design also allows the user to disconnect and reconnect the lead wire without applying excessive force to the sensor or patient. Additionally, the user can strategically apply pressure to the sensor above the gel area when the ECG sensor is to be removed from the patient. Here, the gel spreads and eases the removal of the sensor after successful ECG signal acquisition.

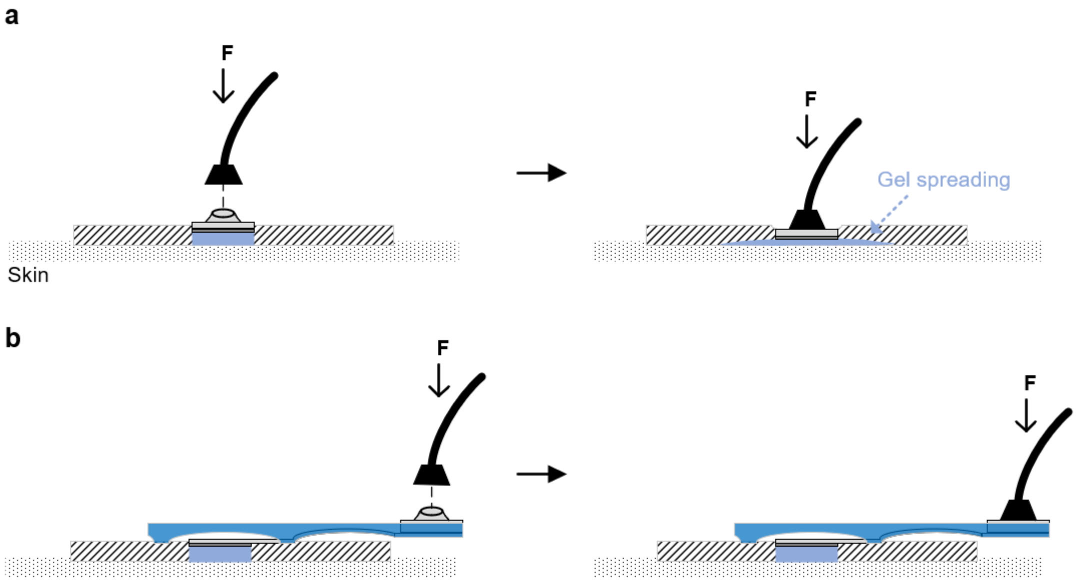

Figure 3*: Schematic illustration of the lead wire being connected to ECG sensors with either center fitting (a) or offset fitting design (b). The lead wire is applied with application force, F, which causes the gel to spread at the skin—sensor interface for the center fitting sensor. The offset fitting allows the user to support the backside of the fitting and connect the lead wire without applying pressure to the patient.*

To test the influence of the sensor design and external forces applied to the fitting, two different commercially available ECG sensors were tested, where the primary difference between the sensors was the design. One sensor type has the center fitting, while the other represents the offset fitting design. A pair of each sensor type were placed in a lead II configuration as illustrated in Figure 4 and the respective ECG signals were recorded. The ECG recordings were performed without noise filters with an *ECGpro CardioPart 12 Blue-P* from AMEDTEC (Germany). During the recording, the fittings of both sensors placed on the upper chest were tapped simultaneously with one hand with approximately 4 seconds intervals. The ECG signal for each sensor type is plotted as a function of time in Figure 4.

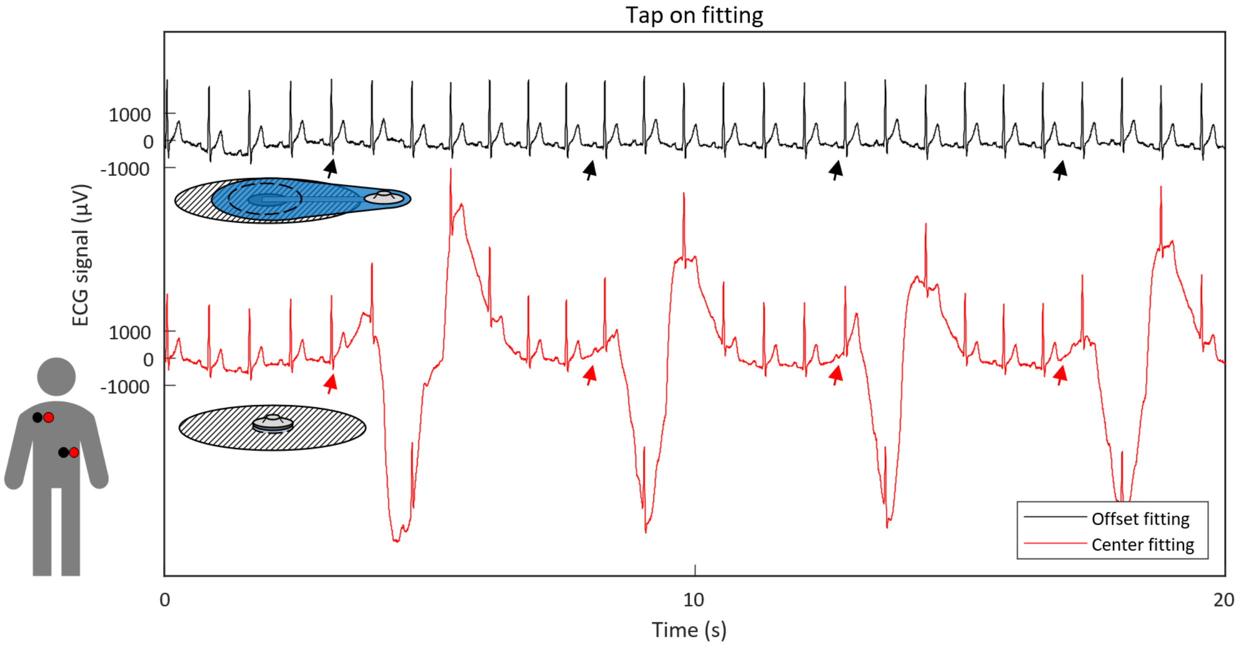

***Figure 4**: ECG signals obtained with respective pairs of ECG sensors with offset fitting and center fitting designs. The sensors were placed on the torso in a lead II configuration. During the recording, the fittings of the sensors placed on the upper chest were tapped simultaneously approximately every 4 s. The arrows indicate the times of each tab.*

The ECG signal at the top of Figure 4 represents the sensors with offset fittings, while the signal at the bottom was obtained with center fitting sensors. The ECG signal changes dramatically for the center fitting sensors during each tap, which are indicated by arrows. Here, the baseline was translated by up to 7000 µV. The signal obtained with the offset sensors was unaffected by the intermittent taps and yielded continuous ECG data.

Pulling on Lead Wires during Wear

Lead wires attached to ECG sensors may be pulled during wear e.g., due to the patient's movements or entanglement of wires and catheters. To explore the effect of lead wire pulling on the ECG signal acquisition with sensors with center fitting and offset fitting designs, pairs of each sensor type were attached in a lead II configuration as shown in Figure 5. The lead wires of the sensors on the upper chest were pulled approximately every 5 seconds with a force of, F_p = 1 N, in a direction perpendicular to the skin—sensor plane (Figure 5). To avoid the influence of biopotentials generated by skeletal muscles, the subject remained at rest while the lead wires were pulled. The recorded ECG signal of each sensor pair are presented in Figure 5, where the arrows indicate the time of each lead wire pull. Prior to the first lead wire pull, the ECG signals of the two sensor types appear identical. After the second lead wire pull, the ECG signal of the offset fitting sensors demonstrate a temporary drop in potential of approximately 1000 µV. However, the signal recovers within 0.1 s from the pull and no translation is observed in the baseline (Figure 5). For the sensors with the center fitting design, the ECG signal exhibits drops in potential varying between 2000-7000 µV immediately after each lead wire pull. Subsequently, the potential baseline drifts by ±1000 µV without fully recovering signal stability before the following lead wire pull. These findings indicate that the biopotential acquisition is perturbed to a much greater extend for the center fitting sensors compared to offset fitting sensors when the sensors are subjected to external pull forces. The reason for the substantial difference in signal noise of the two sensor types can be hypothesized with simple force considerations as illustrated in Figure 6.

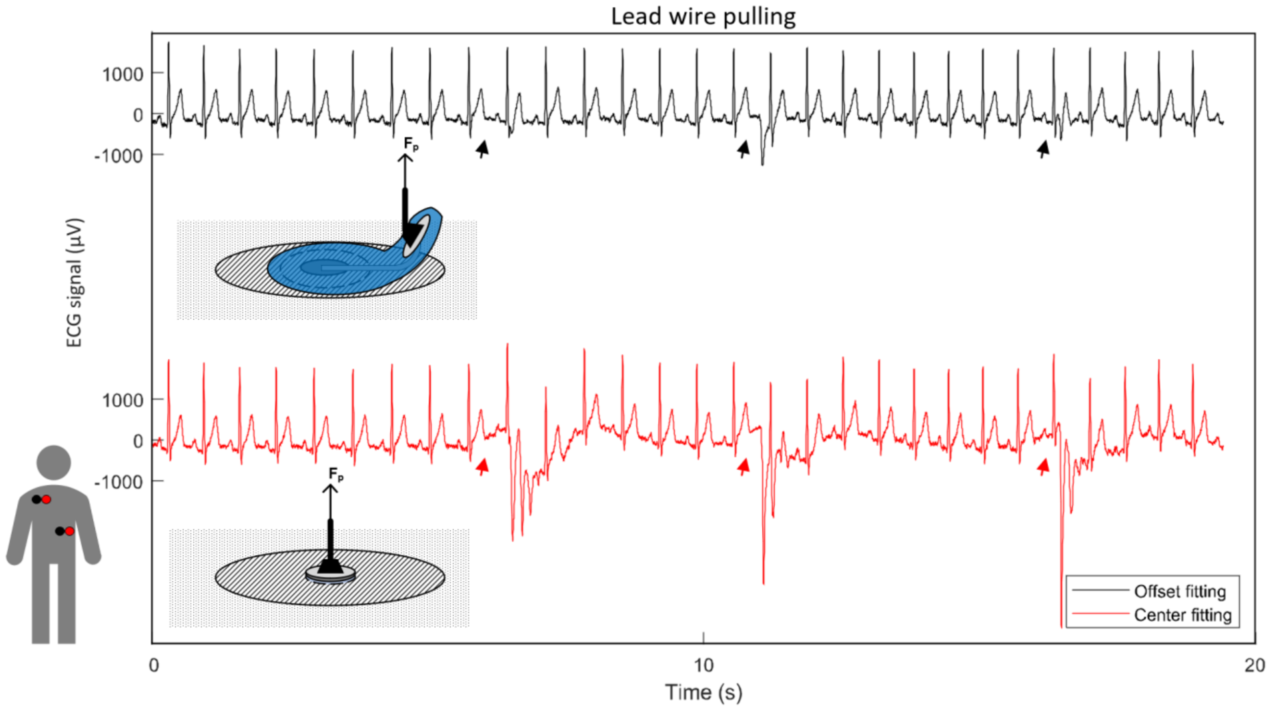

Figure 5: *ECG signals as a function of time for pairs of sensors with either offset fitting or center fitting designs. The lead wires of the sensors placed on the upper chest were pulled with a force of,* $F_p = 1\ N$*, as schematically illustrated. The arrows indicate the time of each lead wire pull.*

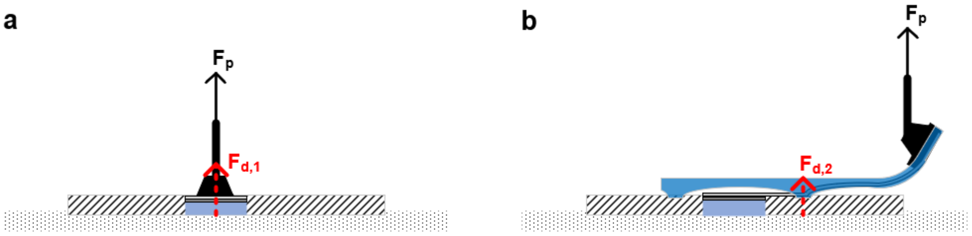

Figure 6: *Cross section of ECG sensors with center fitting (a) and offset fitting (b) design. Each sensor is affected by a lead wire pulling force,* F_p*. The pulling force is partly dissipated in the device depending on its construction before the remaining force is dissipated at the skin—sensor interface. The forces dissipated at the skin—sensor interface in (a) and (b) are denoted,* $F_{d,1}$ *and* $F_{d,2}$*, respectively.*

For the center fitting sensor (Figure 6a), the pulling force, F_p, will propagate through the stiff fitting and Ag/AgCl electrode of the device to the electrolyte gel. For cohesive gels, the force, $F_{d,1}$, will primarily be dissipated at the skin—gel interface (Figure 6a). For a viscous gel, the force will primarily be dissipated at the Ag/AgCl electrode—gel interface. Both these situations are expected to disturb the electrical contact with the skin as the Ag/AgCl sensor and gel are displaced. This will cause artifacts in the ECG signal as revealed in Figure 5. When the offset fitting sensor is subjected to a lead wire pulling force, the force propagates through the offset element to the skin adhesive through the local anchoring on the backside of the skin adhesive. Energy is expected to be dissipated in the anchoring contact line and in the viscoelastic skin adhesive before the remaining force is dissipated at the skin—adhesive interface, which is represented by the force, $F_{d,2}$. The force is thus primarily dissipated at the skin—adhesive interface rather than at the sensor area (Figure 6b). This was shown to yield fewer and less critical artifacts in the ECG signal (Figure 5) and demonstrates the advantage of the offset fitting design.

Conclusion

The influence of external forces on the ECG signal were investigated for ECG sensors with two different designs: The center fitting design, where all electrical components are stacked, and the offset fitting design, where the fitting is strategically placed away from the sensor area. During ECG recordings, the sensors were subjected to both push and pull forces represented by taps on the fittings and lead wire pulling, respectively. The ECG signal, of the sensors with center fitting design, were in all cases disturbed by the forces and dramatic drops in potential and baseline drift were observed. The sensors with the offset fitting design produced undisturbed ECG data, which proved their ability to mitigate the influence external forces. Additionally, the offset fitting design allows the user to connect/disconnect the lead wire without the need for applying pressure to the patient or the sensor area, which eliminates the risk of gel spreading and adhesive failure.

References

[1] Kalra, A., *et al. Critical review of electrocardiography measurement systems and technology*. Measurement Science and Technology 30.1 (2018): 012001.

[2] Baik, S., *et al. Bioinspired adhesive architectures: from skin patch to integrated bioelectronics*. Advanced Materials 31.34 (2019): 1803309.

[3] Rattfält, L., *et al. Properties of screen printed electrocardiography smartware electrodes investigated in an electro-chemical cell*. Biomedical engineering online 12.1 (2013): 1-11.

[4] Huigen, E., *et al. Investigation into the origin of the noise of surface electrodes*. Medical and biological engineering and computing 40.3 (2002): 332-338.

[5] Hansen, D., *et al. Performance of polymeric skin adhesives during perspiration*. ACS Applied Polymer Materials 2.4 (2020): 1535-1542.

[6] Rasmussen, J., 1985, *Medical electrode and a method of manufacturing same*. US Patent 4524775A

[7] Clifford, G. D., *et al. The PhysioNet/computing in cardiology challenge 2015: Reducing false arrhythmia alarms in the ICU*. 2015 Computing in Cardiology Conference (CinC), IEEE, 2015.

[8] Mohd Apandi, Z. F., *et al. An analysis of the effects of noisy electrocardiogram signal on heartbeat detection performance*. Bioengineering 7.2 (2020): 53.

[9] Cvach, M., *Monitor alarm fatigue: an integrative review*. Biomedical instrumentation & technology 46.4 (2012): 268-277.

[10] Sandau, K. E., *et al. Update to practice standards for electrocardiographic monitoring in hospital settings: A scientific statement from the American Heart Association.* Circulation 136.19 (2017): e273-e344.

[11] Liu, C., *et al. Life-threatening false alarm rejection in ICU: Using the rule-based and multi-channel information fusion method*. Physiological measurement 37.8 (2016): 1298.