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Influence of Mobile Phones on the Quality of ECG Signal Acquired by Medical Devices

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Health aspects of the use of radiating devices, like mobile phones, are still a public concern. Stand-alone electrocardiographic systems and those built-in, more sophisticated, medical devices have become a standard tool used in everyday medical practice. GSM mobile phones might be a potential source of electromagnetic interference (EMI) which may affect reliability of medical appliances. Risk of such event is particularly high in places remote from GSM base stations in which the signal received by GSM mobile phone is weak. In such locations an increase in power of transmitted radio signal is necessary to enhance quality of the communication. In consequence, the risk of interference of electronic devices increases because of the high level of EMI.

In the present paper the spatial, temporal, and spectral characteristics of the interference have been examined. The influence of GSM mobile phone on multilead ECG recordings was studied. It was observed that the electrocardiographic system was vulnerable to the interference generated by the GSM mobile phone working with maximum transmit power and in DTX mode when the device was placed in a distance shorter than 7.5 cm from the ECG electrode located on the surface of the chest. Negligible EMI was encountered at any longer distance.

Keywords: GSM mobile phone, electrocardiogram, electromagnetic interference.

1. INTRODUCTION

PEOPLE are exposed to a number of potential sources of electromagnetic interference (EMI) in their everyday life, like mobile phones, surveillance devices, home appliances, toy remote controls, etc. Industrial environment can be a source of radiation generated by high voltage power lines, transformers, welders, electric motors, induction furnaces, degaussing coils, etc. In the hospitals many medical devices can produce EMI, e.g., magnetic resonance image scanners, electrosurgery, defibrillation, neurostimulators, radiofrequency catheter ablation, and therapeutic diathermy. There are numerous reports of the influence of various types of radio transmitters on medical equipment [1-6]. Adverse event reports related, inter alia, to EMI between medical devices and wireless communication equipment are available at the special US database [7]. Broad review of the European Regulatory Framework related to EMI of medical equipment is presented in [8, 9]. Mobile telecommunication systems show very large growth rate all over the world as they become an important communication medium. The GSM mobile phone is a potential source of EMI which can affect the reliability of medical devices [10-14]. Evidences of GSM phone’s EMI interference are reported for implanted cardioverter defibrillators (ICD) [15, 16], external cardioverter defibrillators (AED) [17], implanted pacemakers [18-20], cardiac monitors [21, 22], infusion pumps [23, 24], and ventilators [25, 26]. Critical is interference with life supporting devices. Some of the recommendations delivered by researchers prohibit use of mobile phones in hospitals to avoid any possible malfunction of medical devices [27, 28] but others suggest use in the restricted noncritical care areas [29-31].

Electrocardiograms are recorded in many health care units and often represent the first-line of examination undertaken to establish a diagnosis. EMI, like other artifacts, could result in wrong diagnosis leading to inappropriate medical treatment and medical errors [2, 32, 33].

EMI related errors of ECG processing algorithms implemented in stand-alone ECG devices can influence doctor’s diagnosis. Furthermore, such errors may influence algorithms implemented in medical devices, e.g., leading to errors in differentiation between shockable and non-shockable arrhythmia by AED. Studies of interactions of GSM mobile phones with pacemakers confirmed that in order to cause interference the mobile phone had to be closer than 10 cm to the pacemaker pocket [13, 34]. Similar results were obtained for both unipolar and bipolar ECG sensing configurations.

The increased risk of interference caused by GSM phones results from the specific temporal characteristics of GSM system operation. In Time Division Multiplexing modulation the user occupies 1 out of 8 consecutive time slots forming a frame. Each slot has a length of 0.58 ms. This means that a mobile phone emits periodic power bursts with a frequency of 217 Hz. Data are transmitted by the phone at the end of every multiframe period consisting of 26 frames which is connected with power bursts with a frequency of 8 Hz. The peak power of digital phones used in the European GSM system is 2 W and 1 W for 900 MHz and 1800 MHz frequency bands, respectively. Power control system regulates the output radio signal power to the minimum value necessary for effective communication. However, when the user is located at the edge of the cell (far from the base station) or in shielded spaces, e.g., elevators, reinforced concrete structures, the mobile phone may operate at maximum transmit power level. Another mechanism which changes the temporal characteristics of data transmission is Discontinuous Transmission (DTX) mode. This mechanism limits the frequency of power bursts to 2 Hz in periods of voice inactivity. RF bursts sent with frequencies 2 and 8 Hz correspond to 120 and 480 pulses per minute, which in certain circumstances may mimic fibrillation in the ECG signals. However, power of the signal transmitted from the mobile phone changes in the range from 0.02 W to 2 W and it depends on the strength and quality of the signal received from the base station [35-38].

There is strong evidence that mobile phones may produce EMI that adversely affects the operation of ECG systems and may lead to the inability to properly interpret ECG results. In the present paper the influence of the interference produced by the GSM mobile phone operating at 900 MHz frequency on the quality of the multilead electrocardiogram recordings was studied. The mobile phone antenna in respect to the ECG electrode relative location was considered. Spatial, temporal, and spectral characteristics of interference have been examined.

2. SUBJECT & METHODS

The study was performed in the Laboratory for Bioelectromagnetical Measurements and Imaging (IBBE PAS). Hewlett-Packard HP5515A Wireless Communications Test Set, equipped with omnidirectional dipole antenna, supporting GSM network emulation and mobile device testing was used to control the power and mode of transmission of the mobile phone (Nokia N900). Nokia N900 was selected for the study because it was the only mobile phone model available which was equipped with all possible communication systems. The type of the antenna used in Nokia N900, which is critical for the propagation scenario, is used generally, so we suppose the influence will be similar for other types of mobile phones. Mobile phone and Wireless Communication Test Set were located at a distance of 1.5 m. The location of the built-in antennas is shown in Fig.1.

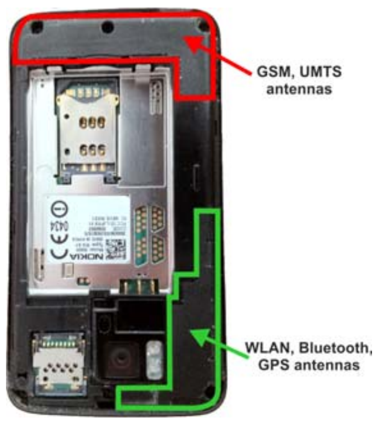

Fig.1. Nokia N900 inside view with battery removed.

Healthy volunteer was examined in supine position. The 67-lead, high-resolution electrocardiographic mapping system was used for ECG recordings [39, 40]. Passive electrodes were positioned around the patient's torso according to the diagram shown in Fig.2. [41]. Three limb leads were used to form the Wilson Central Terminal. Measurements were performed in a shielded room. The ECG signals were digitized with 4 kHz sampling frequency and 16 bits amplitude resolution.

The power of the signal generated by the GSM Wireless Communications Test Set was fixed at -50 dBm which is several orders of magnitude less than the power of a GSM mobile phone. This setting allows suppressing the influence of the emulated base station signal transmitted to the mobile phone on the measurement conditions. All the mobile phone parameters were controlled by the emulated base station. Electrocardiographic maps were acquired during rest with the mobile phone turned off and two modes of mobile phone radio signal transmission:

- Standard connection mode with +33 dBm signal power
- Discontinuous Transmission Mode (DTX mode) with +33 dBm signal power

In both DTX and standard transmission modes the maximum GSM phone transmitted power at 900 MHz was set at +33 dBm, i.e., 2 W so that the tests were conducted under worst-case conditions [23]. The distance between ECG electrode corresponding to the lead number 20 (Fig.2.) and mobile station GSM antenna was changed in the direction perpendicular to the volunteer's chest in the range of 0 cm to 100 cm. Location of electrode number 20 corresponds to position of electrode V2 in a standard 12 lead ECG system.

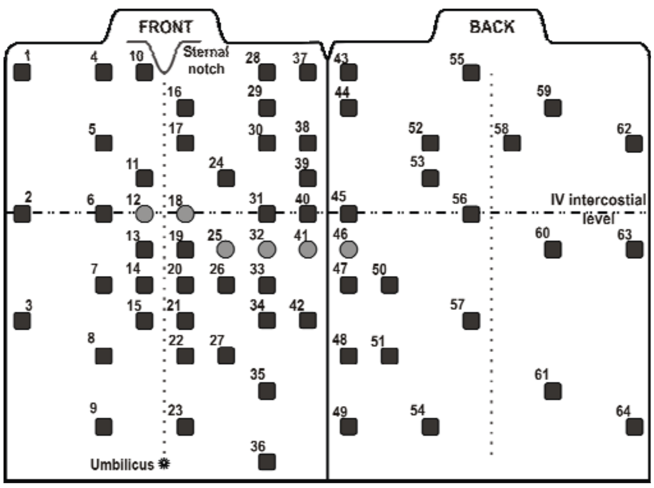

Fig.2. Lead arrangement around the torso. Standard ECG leads are marked by circles.

For further comparison of signals five selected test scenarios were analyzed:

- **GSMoff:** mobile phone turned off
- **GSMon-DTXoff_0cm:** mobile phone turned on (+33 dBm), DTX mode off, distance 0 cm (direct location of the mobile phone on the body surface, GSM antenna located on the electrode corresponding to lead number 20)
- **GSMon-DTXoff_7.5cm:** mobile phone turned on (+33 dBm), DTX mode off, distance 7.5 cm
- **GSMon-DTXon_0cm:** mobile phone turned on (+33 dBm), DTX mode on, distance 0 cm

- **GSMon-DTXon_7.5cm:** mobile phone turned on (+33 dBm), DTX mode on, distance 7.5 cm

The equipment used in the study is schematically shown in Fig.3.

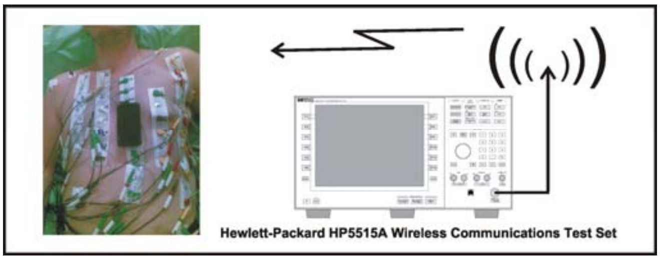

Fig.3. Measurement scenario - schematic diagram.

Separately for each recording and independently in every ECG lead, the noise quantification was performed as follows:

- A part of the ECG signal was selected covering the iso-electric region with a fixed length of 0.25 sec.
- Due to the fact that the GSM interference is expected at frequencies higher than 160 Hz a Butterworth high-pass filter was applied to exclude the slow signal drifts, the ECG content, muscular noise and power supply noise (including harmonics).
- Finally, the noise component was quantified by computing the root mean square (RMS) of the signal for every ECG lead [42].

Typical ECG signal disturbed by GSM interference is shown in Fig.4.

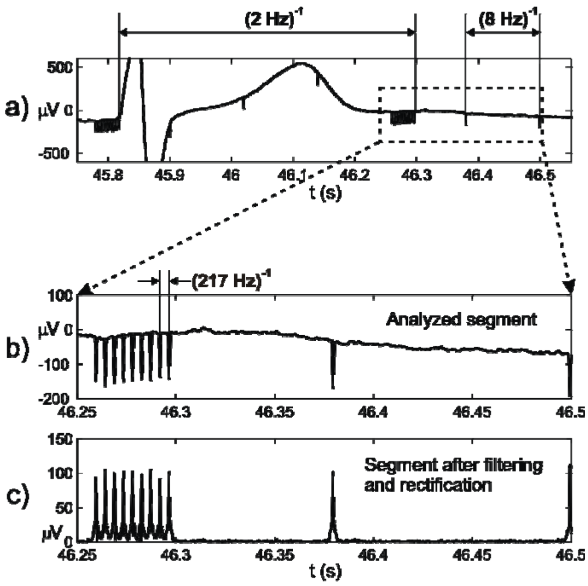

Fig.4. ECG signal measured by lead number 20 which is most affected by the GSM power. Measurement carried out in DTX mode. The mobile phone placed directly on the chest: a) amplified QT interval of the ECG signal showing the interference generated by mobile phone; b) analyzed segment containing bursts with a fixed length of 250 ms.; c) noise segment after high pass filtering at 160 Hz. Diagram.

The RMS values of noise calculated for every ECG lead were used for presentation of the distribution of the GSM interference on the human body. The biharmonic spline interpolation algorithm with Green functions was used for smoothing the obtained maps of noise [43].

3. RESULTS

The highest level of noise was detected in lead number 20 which was the closest to the mobile phone GSM antenna. Segments of the ECG signal recorded in the lead number 20 with well seen mobile phone generated interference for two selected DTX settings are shown in Fig.5. together with the corresponding power spectra. In time domain representation spikes corresponding to the mobile phone data transmission periods can be seen. In GSM normal mode continuous trail of spikes is generated whereas in DTX mode interference appears periodically in bursts.

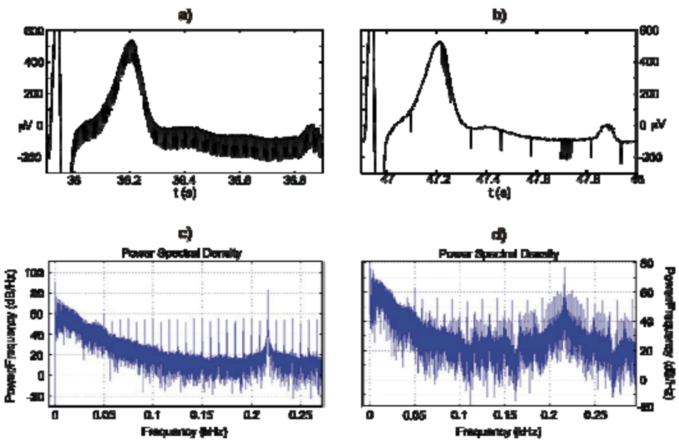

Fig.5. Interference in ECG signal caused by mobile phone (a,b) together with corresponding power spectra (c, d). The mobile phone placed directly on the chest. a), c): GSMon-DTXoff_0cm; b), d): GSMon-DTXon_0cm.

Noise magnitude maps show different distribution of mobile phone generated interference on the body surface. The distribution depends on the mode of activity of mobile phone and its location in relation to the ECG electrodes (Fig.6.). The mobile phone location was marked by a black rectangle. GSM antenna was located in the upper part of the rectangle.

There is obviously no EMI induced by the mobile phone in deactivated mode (OFF) - Fig.6. The average noise in the isoelectric signal in such condition was lower than in the case of activated mobile phone located in close proximity to the body.

The electrocardiographic system was vulnerable to the interference produced by the GSM mobile phone when placed at a distance smaller than 7.5 cm. Mobile phone generated EMI was negligible at all longer distances (noise smaller than 1.6µVRMS). Mean values (averaged in time of 0.25 sec corresponding to ECG isoelectric line) of the noise level were calculated for each measurement scenario. Power of noise is presented in Fig.7. for all considered measurement scenarios.

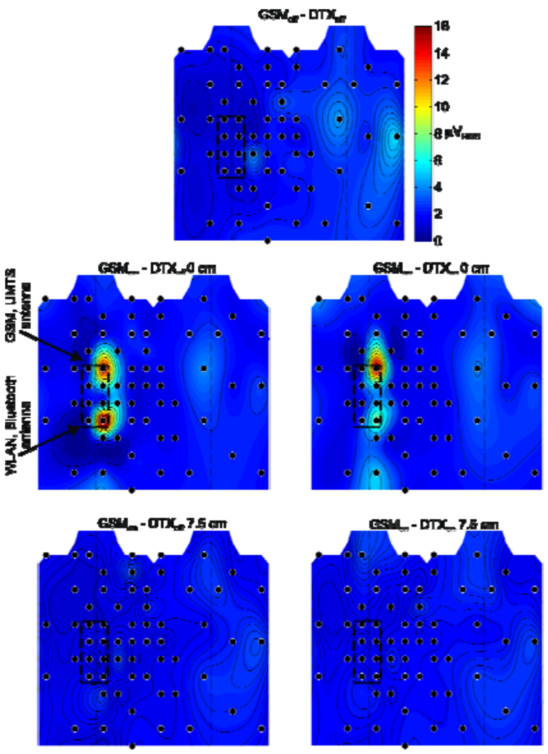

Fig.6. Distribution of the noise magnitude on the body surface calculated from ECG recordings in different electromagnetic conditions connected with the state of GSM mobile station. The black box represents location of the mobile phone.

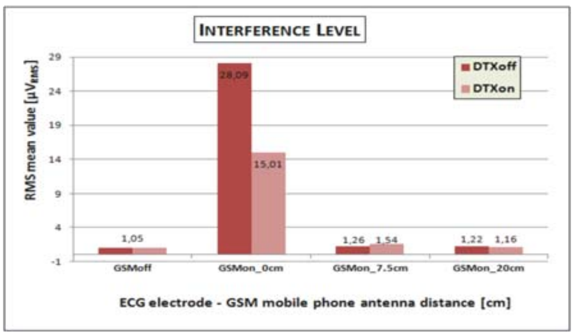

Fig.7. Interference level in signal recorded in the ECG lead located in direct proximity to mobile phone GSM antenna for three test scenarios: GSM OFF (GSMoff) and GSM on in both normal (GSMon-DTXoff_0cm) and DTX mode (GSMon-DTXon_0cm)

To analyze statistical significance of differences between results obtained in different measurement scenarios T-Student test was used. The results are presented in Table 1. As expected, a statistical significance of difference between signals obtained without GSM interference and those with mobile phone working in normal mode was observed. When the mobile phone was in DTX mode the spectral structure of noise was similar to that which is observed when the phone was off. However, the GSM interference was statistically significant when the mobile phone was located directly on the body of the subject. For all considered distances between mobile phone and the body of the subject, statistically significant difference in noise content was observed between normal mode and DTX mode.

Table 1. Statistical separation between mean values of data sets (ns: not significant).

Group 1	Group 2	T-Student test
GSMoff	GSMon_DTXoff_0cm	p<0.05
GSMoff	GSMon_DTXoff_7.5cm	p<0.02
GSMoff	GSMon_DTXoff_20cm	p<0.003
GSMoff	GSMon_DTXon_0cm	p<0.03
GSMoff	GSMon_DTXon_7.5cm	ns
GSMoff	GSMon_DTXon_20cm	ns
GSMon_DTXoff_0cm	GSMon_DTXoff_7.5cm	p<0.008
GSMon_DTXoff_0cm	GSMon_DTXoff_20cm	p<0.005
GSMon_DTXoff_0cm	GSMon_DTXon_0cm	ns
GSMon_DTXoff_0cm	GSMon_DTXon_7.5cm	p<0.04
GSMon_DTXoff_0cm	GSMon_DTXon_20cm	p<0.03
GSMon_DTXoff_7.5cm	GSMon_DTXoff_20cm	ns
GSMon_DTXoff_7.5cm	GSMon_DTXon_7.5cm	p<0.002
GSMon_DTXoff_7.5cm	GSMon_DTXon_20cm	ns
GSMon_DTXoff_20cm	GSMon_DTXon_20cm	p<0.02

4. DISCUSSION

Based on the study result and information from the literature it is known that the GSM mobile phone electromagnetic radiation influences the ECG recordings. The strength of the influence is related to the distance between the ECG electrode attached to the torso and GSM mobile phone antenna transmission mode and power level. The level of the electromagnetic interference caused by the mobile phone has been found different for each ECG lead. There was strong relationship between ECG electrode location relative to GSM mobile phone antenna and the magnitude of noise. The measurements carried out showed that the most influenced ECG signal was recorded in lead number 20 corresponding to V2 in standard 12-lead system, which was the closest to the GSM mobile phone antenna. The strongest interference of the electromagnetic field generated by the mobile phone was detected in the situation when the GSM antenna was in direct proximity (distance: 0cm) to the body. There was significant increase in noise level (Fig.7., conditions: GSMon-DTXoff_0 cm, GSMon-DTXon_0 cm). When the mobile phone was removed from the body the power of noise was significantly lower and in some cases even negligible. There is no statistical difference between mean values of RMS noise magnitude recorded in DTX mode for distances longer than 7.5 cm and those recorded with the mobile phone turned off. At these distances between the mobile phone and ECG electrode the noise is small enough to make the ECG signal dominant.

7. CONCLUSION

The study shows the worst case level of the interference induced in ECG electrodes located on the surface of the human body. The strength and the propagation pattern depend on the design and location of the mobile phone GSM antenna. The influence of the interference on the ECG acquisition system depends also on the design of the electrode leads and electronic circuits used for ECG amplification and acquisition. Though the present study has been done for one particular set of the equipment which includes GSM mobile phone and electrocardiographic system, findings relating spatial distribution of interference and its effect on the quality of recorded ECG signal reflect general relationship.

It has been shown that during ECG recordings mobile phone should be turned off or it should be located at a distance longer than 7.5 cm from any of the ECG electrodes to prevent artifacts in the electrocardiographic signal. It should be noted that even when the mobile phone is not used for any voice or data communication it is periodically transmitting low frequency bursts. The noise level in DTX mode is lower but its temporal characteristics may cause problems because its pattern in ECG signal may mimick fibrillation events. Influence of mobile phones on ECG acquisition systems may depend on the method of the ECG signal analysis implemented. Special attention should be paid to the potential susceptibility of AED algorithms.

Electromagnetic susceptibility of medical equipment depends also on numerous factors related to electric and mechanical design (shape, size, materials used, effectiveness of shields and filters, etc.). Further studies are required in order to assess the EMI of GSM mobile phones for specific groups of medical products.

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