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REVIEW

Effects of electromagnetic interference on the functional usage of medical equipment by 2G/3G/4G cellular phones: A review

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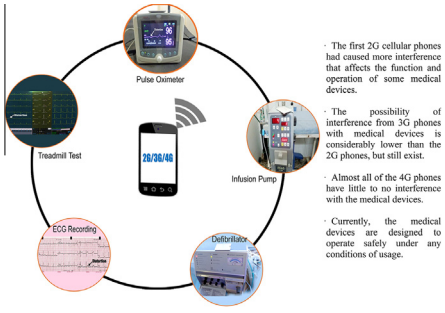
GRAPHICAL ABSTRACT



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ABSTRACT

There has been an increase in the potential use of wireless devices in healthcare domain for a variety of reasons. The most commonly used device is the cellular phone, which emits strong electromagnetic energy affecting thereby the functionality of the vital medical equipment such as ventilators, ECG monitors, cardiac monitors, and defibrillators. This prompted the healthcare concerns to restrict the use of these phones in the proximity of critical and

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non-critical care medical equipment. Due to the developments made in the design of medical equipment to comply with the EMC standards, the restriction had been slowly laid off. Still, the researchers are concerned about the electromagnetic interference with medical devices by cellular phones in the healthcare domain and recommend for conducting continuous research to study their interaction with medical equipment. This paper overviews the certain investigations carried out in the recent years to study the electromagnetic interference between medical devices and 2G/3G/4G LTE cellular phones. During the initial development of cellular phones, the 2G cellular phones had caused more interference that affects the function and operation of some medical devices. The possibility of interference from 3G cellular phones with medical devices was considerably lower than the 2G phones, but still exists. Furthermore, almost all of the 4G phones have little to no interference with the medical devices. Currently, with the development of the medical devices industry, the current medical devices are designed to operate safely under any conditions of usage. Finally, a careful analysis would require statistics on the frequency of adverse events across the healthcare system, which apparently do not exist.

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Introduction

Cellular phones provide a convenient mean of communication to every walk of life in the society [1–4]. During the two past decades, there has been a significant increase in customers who prefer this technology for their personal communication. The accessibility, ease of use, and low cost of these phones resulted in electromagnetic (EM) pollution [5–10]. In healthcare, patients tend to use cellular phones at their bedside to communicate with their relatives and friends during their treatment [11–15]. Moreover, doctors, staff members, and nurses make the best use of cellular phones not only for their personal use, but also for the purpose of healthcare services [16–18]. Consequentially, EM radiation from different radio sources in the hospitals has arisen. According to the literature, a cellular phone emits a peak amount of power not only during the ringing phase [19,20] but also during its standby mode [21].

Studies [22–53] revealed that the cellular phone is one of the potential sources of interference to the working of many numbers of medical devices. The radiation from cellular phones will either make the nearby medical device malfunctioning or alter the parameters measured. Moreover, it could make changes in the monitors. In the literature, most devices vulnerable to the cellular phone radiations are the mechanical ventilators, infusion pumps, Electrocardiogram (ECG) recorder, patient monitors, defibrillators [54–56], and pacemakers [57–

62]. Meanwhile, the alteration of measured parameters may change the diagnostic process that may lead to improper treatment [63]. As a consequence of these facts, hospitals around the world banned the use of cellular phones in the critical care units or emergency departments [64]. This prohibition has been gradually lifted off during the course of time, since some changes had been made in the design of medical devices to have better immunity to EM radiations from cellular phones. The evolving standard designed for better EMC compatibility of medical devices to cellular phone radiation is the EN60601-1-2, which is the revised version of International Electrotechnical Commission (IEC) Standard 60601-1-2. This increases the immunity level of non-critical care and critical care devices to 3 V/m and 10 V/m respectively as well as the frequency of operation is extended to 2.5 G*Hz* [54]. Additionally, the medical devices should be protected with better shielding materials to protect them from any kind of EMI. Furthermore, in order to enhance the quality of service, hospitals are utilizing other wireless devices such as the Radio Frequency Identification Devices (RFID) for the purpose of patient identification, asset tracking, and monitoring patient care to reduce innumerable medical error and for infant – mother matching. Similarly, Wireless Local Area Networks (WLAN) are employed in hospitals for monitoring patient's vital parameters such as ECG, heart rate and blood pressure; then, they are sent to the central monitoring system in the hospital to check patient's health continuously. Literature revealed that employment of the devices such as the RFID readers and WLAN devices also caused malfunctions in the nearby medical devices [65–79]. Thus, care must be taken to ensure that these devices be kept at an adequate distance from these EMI sources to avoid inadvertent events of EMI in the medical devices.

Consequent to the relaxation in banning the usage of mobile phones in the hospital, patients, visitors, or nurses are allowed to use their cellular phone to 2 m apart from the concerned medical devices [54]. This has been further relaxed to be at a distance of 1 m. Researchers cautioned that the rapid changes in the technology of the cellular phone, or medical equipment, might mitigate the interference from cellular phones. But, sometimes they worsen the situation! So, it is essential to carry out the testing of medical devices in the hospitals to verify whether the radiation from the new radio devices interferes with them, or not. The results obtained will help the hospitals to check out Electromagnetic Interference (EMI) policy on their premises.

The EMI on medical devices by cellular phones depends on various factors, including power emitted by cellular phone, the frequency of operation, the distance between the cellular phone and the medical device, mode of operation of the cellular phone, and the immunity of the medical device concerned [68]. The malfunctioning of medical devices ranges from distortion in monitors, noise in ECG recordings, switching-off the devices, resetting of the devices, and alteration in flow rates. All these changes in the functioning of the medical devices are called as EMI incidents. Depending on the type of EMI incident occurred, it can be classified as, light or significant or hazardous [71]. According to Food and Drug Administration of USA [80], the light event is defined as an effect on monitoring with little attention required. Similarly, a significant event is defined as an effect or impact on monitoring with a substantial attention needed to make the considerable level of destruction in patient diagnosis. Finally, the hazard is defined as a direct physical on the patient by an unintended change in equipment function. The devices exhibit hazardous or significant events either at short or at long distances from Radio Frequency (RF) sources, and particularly cellular phones, should be kept away from all possible RF sources in hospitals. This may reflect the poor effectiveness of shielding of the concerned medical devices. Devices that have a long measurement lead such as ECG monitors are susceptible to EM radiations from both Second Generation (2G) and Third Generation (3G) cellular phones and may cause a significant EMI event when they are kept in close proximity. Accordingly, this work overviews the literature concerning the EMI of various kinds of cellular phones such as 2G, 3G, 4G LTE, two-way radios and walkie talkies, and the medical devices that belong to the critical care and the non-critical care categories.

Material and methods

The literature for this study is based on many searches in various databases including IEEE Xplore digital library, MEDLINE database, and Elsevier digital library, and from the research available through Google Scholar. The index terms used for searching these databases were "EMI in medical devices by cellular phones", "Cell phone interference in medical devices", and "EMI, Medical Devices, and Cellular Phones". Nearly 200 publications were taken from these databases. Only the articles written in the English language were considered. Regarding these publications, articles concerning about EMI between cellular phones and critical care devices as well as monitoring devices were considered. The impact of cellular phones on other devices such as auditory devices and ophthalmologic devices was not considered in this study. This literature is organized in chronological order based on the year of publication, and a systematic review was performed. Furthermore, the entire literature is divided into two categories. The first one is the EMI between non-critical care devices and cellular phones. The second one is the EMI between emergency care, ICU devices, and cellular phones.

EMI between critical care devices and cellular phones

Evaluation of EMI between critical care devices and cellular phones is essential for various reasons. Most of the studies have concentrated on these EMI issues in different aspects, i.e. studies involved with different types of cellular phones, various operating modes of cellular phones and the environment at which the full evaluation has been carried out. In general, the evaluation had been performed on-site (ad hoc test) where the equipment is located since it provides the actual outcome of the EMI test with varying environments. At the same time, this on-site ad hoc test will not reflect the actual EMI performance of the devices since the EMI effect was also influenced by various factors, including some nearby wireless transmitters, and the presence of reflecting materials near the medical devices.

Hanada et al. [81] analyzed the EMI between medical equipment and the Personal Handy-phone System (PHS) handsets, which is very common in Japan, for both voice and data communication (ad hoc test). It used 1.9 G*Hz* as the operating frequency and had a peak output power of

80 mW that was considerably low compared to the peak output of a cellular phone. The study monitored the mutual EMI between 2 phone handsets, cordless phone and PHS, and 25 pieces of medical equipment that had been in use in the Intensive Care Unit (ICU). The results illustrated that the PHS handsets did not have any EMI with medical devices, and the functioning of medical devices was not affected by the PHS. The results of the study pointed out that although the PHS handsets are safe to be used in hospitals, the close location of PHS base stations to the hospital buildings may cause interference in the medical devices.

Two studies have examined the EM susceptibility of Automated External Defibrillators (AED) with cellular phone radiation in various working modes [82,83]. Karczmarewicz et al. [82] conducted a test to observe the interference in AED during three modes of operations of a cellular phone, such as Discontinuous Transmission (DTX) mode, connection setup, and standard connection. As far as results are concerned, no cases of interferences were observed in the ECG pattern recorded in the AEDs during all modes of operations of the cellular phones. Trigano et al. [83] observed the interference in AED during the ringing phase of the cell phone. Similarly, no disturbance was observed during the ECG recording of the defibrillator and the only disturbance noticed was the noise generated by the AED speaker when the cellular phone was kept close to AED.

On the other hand, Tri et al. [64] evaluated the potential EMI that occurred between four different technologies of 6 cellular phones such as Global System for Cellular Communication (GSM), Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), analogue and 16 numbers of medical devices. Totally, there were 510 tests conducted (ad hoc test). The results revealed that EMI was observed in 108 tests as well as malfunctions, and abnormalities were noticed in 7 devices. The authors concluded that periodical evaluation of EMI with medical devices by cellular phones was required to know their effects accurately. Fung et al. [73] examined the interference with medical devices in critical care units by studying emissions from 3 different cellular phones kept at three different distances. Multiple numbers of medical devices were involved in this ad hoc test. The test results revealed that only the CO_2 airway adapter and the haemo-glucostix meter were disturbed when a cellular phone was in close proximity. Even though the EMI observed was clinically insignificant, the authors concluded that a thorough study is required to assess the policy of using cellular phones in the critical care units and its restrictions.

The electromagnetic interference immunity of ventilators to radiations from different wireless devices was observed in different studies [84–86]. Shaw et al. [84] took a GSM 900 MHz cellular phone as an interference source. Jones and Conway [85] and Dang et al. [86] considered GSM 900 MHz cellular phone and two way radios for their tests. In addition to that, Dang et al. [86] considered the interference by the TDMA phones. In all these studies, the test was conducted following the American National Standard Institute (ANSI) recommended practice ANSI C63.18-2014 for on-site ad hoc testing method for the immunity of medical devices to radio transmitters. The number of ventilators undergone the evaluation in each study was 14, 5 and 7 respectively. According to the results obtained, only one ventilator exhibited light interference by the GSM 900 MHz cellular phone in the study by Shaw et al. [84]. Similarly, only one ventilator was slightly interfered by both the GSM 900 MHz cellular phone and the two way radios in the study by Jones and Conway [85]. However, one ventilator was slightly interfered by GSM 900 MHz phone and all the 7 ventilators are interfered by the two-way radios at closer distances in the study by Dang et al. [86].

Van Lieshout et al. [87] assessed the EMI between critical care medical equipment and a new generation of cellular phones under a controlled environment (bench test). This study included a total of 61 medical devices under 27 categories. The signals used for the tests were the Global Packet Radio Service (GPRS) of 2 GSM phones operating at 900 MHz and a Universal Cellular Telecommunication System (UMTS) signal at 1800 MHz. The results exhibited that higher number of devices was considerably affected by the GPRS signals causing a higher number of hazardous incidents than the UMTS signal. It was also noticed that the median distance for all types of EMI incidents was 3 cm. Based on the results presented, the authors have recommended keeping cellular phones at 1 m distance from a critical care medical equipment.

Hans and Kapadia [88] tested the EMI between specific ICU devices and different working modes of GSM and CDMA phones. The devices considered in this study were a syringe pump, a mechanical ventilator, and a bedside monitor. The tests were conducted in rooms, where the devices were accommodated. After several trials, it was found that only one infusion was affected by the GSM phone in talk mode and the other devices were unaffected by the other modes of GSM and CDMA phones. The authors concluded that even though adverse events are not noticed, it is recommended to keep cellular phones one foot away from critical care devices. Also, Iskra et al. [89] investigated the effect of EMI on critical care equipment resulted from GSM 900/1800 MHz, 1900 MHz Wide Code Division Multiple Access (WCDMA) wireless system and 80% AM 1 kHz radio signal. The tests were conducted as per the ANSI C63.18 in a semi-anechoic chamber with balanced half wave dipole replacing the actual handsets (bench test). The devices included in this test were a pulse oximeter, a blood pressure monitor, a patient monitor, a humidifier, a defibrillator, and infusion pumps, representing the set of pieces of medical equipment used in the ICU. The results highlighted that the medical devices are more immune to high-frequency WCDMA handsets than that of the GSM or GPRS handsets when they work at maximum power. The nature of interferences occurred in this test was annoying flicker, distortion or spikes on traces on screen, drift in the baseline, a buzz in speaker or device operation halted in the failsafe mode.

Tang et al. [54] evaluated the EMI susceptibility of 532 critical care devices under 10 categories with 3 different cellular systems such as 2G, 3G, and PCS 1800. This ad hoc test was carried out in 3 different hospitals in Hong Kong. It was found that 9 devices under 6 categories were susceptible to EMI from 2G cellular phone. Only one device was found to be susceptible to EMI from 3G cellular phones. Also, it was observed that 8 devices under 5 categories found to be susceptible to EMI from PCS 1800. The results indicated that the critical care devices are more sensitive to EMI from 2G and PCS 1800 systems than the 3G phones. The study highlighted that the 3G cellular phone may be an appropriate option for hospital staff and doctors for their voice and data communications.

Helhel et al. [90] investigated the immunity of medical devices used in healthcare from the radiations of 2G and 3G cellular phones. The entire test was conducted in the hospital environment where the actual devices were kept. The test was carried out in ad hoc manner as per the guidelines mentioned in ANSI C63.18.16 medical pieces of equipment were tested including ECG monitor, intensive care monitor, ultrasound equipment, X-ray equipment and dialysis equipment. The numbers of devices affected by 2G cellular phone are four and three devices were affected by 3G cellular phones. The maximum distance at which the interference observed for 2G cellular phone and 3G cellular phone is 1.5 m and minimum distance at which interference observed for 2G cellular phone, and 3G cellular phone is 0.5 and 0.35 m, respectively. Ultrasound equipment is the device affected by both 2G and 3G cellular phones at greater distance. During this study also, the acquisition of ECG signals was affected by proximity of both 2G and 3G cellular phones. This is incompatible with earlier studies stating that devices having longer leads or electrodes can easily be affected by radiations from cellular phones.

Hatara et al. [91] investigated EMI between different types of critical care devices used in ICU unit and 3G cellular phones including Long Term Evolution (LTE) phone. This study has critically analyzed the relationship between the occurrence of EMI in medical devices and the different parameters of mobile phones including radiation power, the frequency of operation, the mode of transmission (continuous vs. discontinuous) as well as the distance between the mobile phones and the medical devices. This study was performed as an ad hoc test following the procedures laid out in ANSI C63.18 as well as EMCC and MIC of Japan. During the test, the backside of the mobile phone was oriented toward the medical device since the backside of the mobile phone is emitting the maximum power. The results have shown that 2 medical devices have exhibited EMI from the 32 medical devices that undergone the evaluation. The revelations obtained from the results pointed that the emitted peak power from the mobile phone and the distance between the mobile phone are the significant factors to induce EMI in the medical device. Devices emitting higher nominal power produced more number of EMI incidents at the greater distance than the devices emitting a lower power. Also, it was found that the frequency of cellular phone did not have an influence on the occurrence of EMI in medical devices. It was observed that discontinuous modes of transmission of cellular phones have caused more EMI than the continuous mode. Similarly, the half-wave dipole antenna emitted a higher amount of electromagnetic fields than other mobile phones tested.

Salceanu et al. [92] analyzed the EMI in neonatal ventilators used in ICU unit by the radiation from DECT phone and microwave oven (ad hoc test). This was done because of the frequent change that occurs in the tidal volume of the baby ventilator. The measurements in the ICU unit indicated that a higher density EM radiations in the frequency band of DECT phone and microwave oven were present. The test was conducted in the ICU with other devices switched off. A spectrum analyzer was used to measure the peak power radiated by the radiating sources. The results have shown that a minor abnormal response was observed in the baby ventilator whenever it was placed between the DECT phone and its base station. At the same time, an unexpected high EM radiation was observed from the microwave oven. The authors concluded that it was better to avoid the use of the DECT phones and microwave ovens in the vicinity of neonatal ICU to avoid any unexpected outcome from the medical devices. Also, Duan [93] found that the proximity of the digital cellular phone during ECG recording of the patient has altered the QRS complexes in the observed ECG. It leads to the interpretation that the patient has ventricular tachycardia. After cautious check, it was found that the patient was playing with gaming console on a cellular phone while recording the ECG! Normal ECG was observed after removal of mobile phone from the ECG recording room.

Trigano et al. [20] investigated the reliability of EM filters of pacemakers during the ringing phase of cellular phones since a cellular phone emits peak radiated power during its ringing phase. Nearly 330 tests were conducted among 158 patients during their routine check-up (case study). Two cellular phones were utilized for this purpose. One was a GSM phone operating at 900 MHz, and the other one was a PCS system operating at 1800 MHz. During the test, a cellular phone was placed in the pocket of the patient and call was made to that phone. The results exhibited that only 5 tests were shown minimal interference, which was attributed to naked models of pacemakers. Apart from these 5 incidents, all the peacemakers tested were completely immune to EM radiations from cellular phones during their ringing phase.

Periyasamy and Dhanasekaran [94] investigated the immunity of a particular group of medical devices under the categories of both critical and non-critical care during the ringing and the conversation phase of 2G and 3G cellular phones. The equipment undertaken in this ad hoc test was including a pulse oximeter, ECG recorder, ultrasonic fetal heart detector, ventilators, and defibrillators. The study was conducted according to the ANSI C63.18 recommendations. The results indicated that all the monitoring devices having long leads such as ECG recorders, pulse oximeters, and treadmills are sensitive to EMI from both 2G and 3G cellular phones during their ringing and conversation phase. At the same time, the other devices were insensitive to the EMI. Though the EMI incidents were observed, it occurred at closer distances with minimal effects on the devices except in one case with the ECG recorder was ceasing to operate.

Ismail et al. [95] evaluated the EM susceptibility of pacemakers to the radiations from 3G cellular phones (UMTS). The study was performed on 100 patients who have implanted with permanent pacemakers (case study). The study was conducted with two numbers of UMTS cellular phones in three different working modes such as standby, dialing, and conversation. All the pacemakers were conditioned to work under worst case conditions. ECG patterns from the pacemakers were observed for the interference. All the tested pacemakers have shown complete immunity to radiations from 3G cell phones, and they were safe to use in proximity to the pacemakers.

Regarding the 4G phones, Burri et al. [96] investigated the EM susceptibility of Implantable Cardioverter Defibrillators (ICD) to the radiation from 4G phones. The test was performed on 69 patients (case study) who were carrying 29 models of cardioverter defibrillators from five makers. Two different models of recent 4G phones were used for this purpose. In each test, the smartphone was kept on the ICD generator in three different working modes such as dialing, standby, and operational mode. During each test, the artifacts appeared on the generated ECG were observed. None of the ICDs have

shown interference in their operation, and no cases of noise have emerged in the recorded ECG. It was seen from the results that the 4G smartphones did not interfere with the functioning of the ICDs since the 4G phones emit less power as well as the established filters in the ICDs models.

EMI between monitoring devices and cellular phones

Brande and Martens [97] found that while recording ECG of a patient having a history of coronary bypass surgery, the automatic ECG diagnostic algorithm has shown that the patient had an atrial flutter with a very high atrial rate of 315 beats per minute (case report). In the earlier diagnosis, the patient had no abnormalities in his ECG pattern or his palpitations. After careful investigations, the authors found that one of the family members had a cellular phone in a standby mode at a distance of 1.5 m from the ECG recorder, and that could be a reason for the observed abnormalities in the ECG recording. As the family members were gone away from the emergency ward, the ECG records had shown a normal sinus pattern. The authors concluded that the cellular phones are sources of interference to the ECG recording and that they should be kept away from nearby ECG recorders at a considerable distance.

Calcagnini et al. [98] investigated the EMI effects from GSM phones, Wi-Fi antennas, and Digital Enhanced Cordless Telephone (DECT) phones on infusion pumps, and estimated the safety distance as well as the safe power at which no interference was occurring. The cellular phone was set so that it radiated its maximum power and it was free to move around the equipment in all the accessible positions. The results indicated that only 5 out of 17 pumps were affected by the GSM phones of either 900 MHz or 1800 MHz. The shutdown of the pumps and the stop of flow of the fluid with and without alarms were the types of the malfunction occurred. The occurrence of different EMI incidents was credited to the specific infusion pumps and the electronic circuitry inside the pumps.

Alliyev et al. [99] observed that a charging phone sharing the same electrical socket with a test equipment could create a disturbance in the ECG recording, and that could be interpreted as tachycardia (case report). After careful investigation, the patient was re-examined with another ECG machine, and it was found that the patient had no history of tachycardia.

Buczkowski et al. [100] examined the possibility of interference in ECG recording while the GSM cellular phone was operated in DTX, normal, and deactivated modes (ad hoc test). During the DTX mode, the cellular phone emitted frequency power bursts of 2 and 8 Hz corresponding to 120 or 480 pulses per minute that mimics atrial fibrillation during ECG recording. The tests were conducted with an aid of base station blasters, a GSM cellular phone and ECG recorder connected to the patient. With the help of power settings and control panel in the base station blaster, the cellular phone was set to radiate the maximum amount of power and operate in DTX and normal modes. Based on the results obtained, it was found that during DTX and normal modes, a considerable level of disturbance was observed in the ECG recording through lead number 20. The magnitude of interference increases while decreasing the distance. The authors concluded that the severity of the interference during ECG recording depended on the distance between electrodes and cellular phone as well as circuitry inside the electrode system.

The effect of radiations from 3G cellular phones on the recording of EEG was analyzed in the study by Roggeveen et al. [101] and effect on EEG as well ERP recording by 3G phone was analyzed in the study by Stefanics et al. [102]. The test was involved with human volunteers in both studies. During EEG recording of each participant in the study by Roggeveen et al. [101], a 3G cellular phone was kept in silent mode so that the candidates are not aware of the incoming call. Then, a sham phone was kept in the chest, and ear of the each candidate and the same procedure was followed. The EEG recording of each participant was stored for further computer processing. Each EEG recording was statistically analyzed using SPSS software for the potential presence of interference. The results have confirmed that the placement of cellular phones near to the ear has a detrimental effect on the recording of the EEG than the cellular phones placed near to the chest; this pointed out that as the distance from the brain increases, the impacts of the cellular phones on the EEG recording decrease. In the study by Stefanics et al. [102], twenty-nine human volunteers participated in the test. During the ERP recording, 3G mobile phone was kept nearer to the volunteer and effects on the recording were observed for 20 min of duration. From the results of the ERP recording, it was found that the ERP recording not interfered.

Trunk et al. [103] studied whether the emissions from the 3G phones had an impact on the EEG recording of the human brain or not (case study). During the EEG as well as ERP recordings, the human volunteers were requested to watch a silent documentary film. In each experiment, the mobile phone was kept near to the volunteer for 30 min approximately. After the study, it was observed that none of EEG recordings interfered by the placement of the 3G phones near the EEG recording facility. Also, in the study by Kleinlogel et al. [104], the interference in the recording of ERP by the radiations of both 2G and 3G cellular phones was studied (case study). Two types of cellular phones such as 900 MHz and 1950 MHz UMTS were considered for this study. The results validate that the presence of 2G and 3G phones did not interfere with the recording of the ERP.

Barutcu et al. [105] studied the potential effect of EM radiations from the cardiovascular devices and thus thereby changing the measured parameters or not (case study). Fifteen male volunteers were included in the test. During the ECG recording, each participant was tested in a supine position and mobile phone was operated at three different working modes. They were turned off, turned on, and kept at the calling mode. In each mode, the mobile phone was held for 5 min of duration. It was noticed that the measured cardiac parameters not interfered by phone radiations.

Hurstel et al. [106] and Sidhu et al. [107] examined the possibility of electromagnetic interference between 3G cellular phones (Bench test) and Electronic Apex Locator (EAL) used by dentists during root canal therapy for measuring working length. Hurstel et al. [106] utilized twenty-six human premolars for this purpose. Two numbers of 3G phones were used. During each test, the cell phone was kept on the surface of EAL in two different modes of operation: standby and call making. During all the tests, it was observed that none of the mobile phones induced EMI in the EAL and it provides the freedom to the patients to keep cell phones in their shirt pocket during root canal therapy. Sidhu et al. [107] utilized one of the latest smartphones for this purpose. Fifteen teeth premolars were

prepared for this study. The test protocol consists of the following steps. During each teeth therapy, keep the mobile phone on the surface EAL and operate the mobile phone in calling mode for the duration of 25 s. Then, keep the mobile phone at the distance of 40 cm from EAL and proceed in the call mode for the duration of 25 s. In each case, the change in the EAL is observed. From the results obtained, it was observed that the 3G cellular phones have no effect on the performance of the EAL. Hence, it can be used safely by the patients during their teeth treatment.

Finally, a summary of the different research works undertaken on the EMI with medical devices by 2G/3G/4G cellular phones, is given in Table 1. It is observed that 2G cellular phones had a strong influence on the functioning of the medical equipment than other cellular phones. However, the 3G/4G phones and the PCS devices are found to be less interfered with the medical devices.

Discussion

This study reviews the EMI in medical devices of various types of wireless devices such as 2G and 3G/4G cellular phones at different operating modes, two-way radios, UMTS phones, WCDMA phones, and PHS devices. Also, the effects of the GPRS signal of 2G, and 3G phones on various medical devices were observed. From the literature, it was observed that a cell phone generates significant power even during standby mode. At the same juncture, it generates a higher amount of power during the ringing mode, call initiating phase, and while receiving weak signal strength from the base station. As far as cellular phones are concerned, 2G cellular phones emit high and variable amount of peak power (maximum 2 W) than the other wireless services such as 3G, TDMA, two-way radios, and the PHS cordless phones. Thus, 2G cellular phones may have a strong influence on the functioning of medical equipment than other cellular phones. This is the explanation that the studies concerned with the EMI effects by 2G cellular phones during the 2000s. In addition, during the initial development of the digital cellular phones, 2G was the first technology deployed for voice and data communication.

The studies have proved that critical care devices such as ventilators and infusion pumps are significantly affected by the 2G cellular phones before the development made in the design of medical devices to have better immunity. In the early and mid-2000s, this prevented the use of the 2G cellular phones in close to the ventilators. Similarly, the radiations from 2G cellular phones had the capacity to alter the algorithms in AED since the treatment is given to the patient based on the ECG pattern generated in the AEDs and these ECG patterns were altered by radiations of 2G cellular phones. Almost all the studies have observed that EMI incidents in AEDs are either light or negligible except one study where the AED experienced a hazardous incident. Even though a hazardous incident was observed with the AED, however, it is desirable to keep the 2G cellular phones away from AEDs. Infusion pumps (IP) are one of the most commonly affected medical devices in the various studies, as they have shown different responses in different studies, ranging from the shutdown of pumps, passing with changes in flow rates and ending with changes in the display settings. In some of these studies, infusion pumps are greatly immune to radiations from both 2G and 3G cellular phones.

Besides, devices carrying longer leads such as ECG monitors, patient monitors, and pulse oximeters are greatly affected by the presence of cellular phones of both 2G and 3G categories [100]. Some studies have proved that the unnoticed presence of cellular phones near the ECG recorders or a treadmill equipment has altered the ECG pattern; accordingly, if physicians do not properly notice such phones, patients may get improper treatment. Similarly, pulse oximeters have got affected by the proximity of cellular phones [89]. During the discontinuous transmission mode, cellular phone emits peak bursts of 2 Hz and 8 Hz. If signals of such types affect the ECG recorder, then it may mimic the tachycardia in the recorded ECG pattern. In general, the studies concerning EMI between measurement devices with electrodes and cellular phones proved that the intensity of interference increases with the decrease in distance between the electrodes and the cellular phones. Hence, to avoid the interference, it is desirable to keep off the cellular phones at close distances from measurement electrodes than the measurement system itself. On the other hand, other studies have emphasized the fact that 2G cellular phones are no more a source of threat to the functional usage of medical devices since most of the disturbances observed in the medical devices were light in nature [87,94]. The EMI incidents have occurred at closer distances in the range of centimeters than the meters; this would have reflected the better EMC of the devices concerned than the devices tested in the early and mid-2000s.

Usually, the 3G cellular phones are used in the hospitals by patients and doctors for better voice and data communication. The radiations from these phones are also affecting the performance of the medical devices. The clear distinction between 2G and 3G cellular phones is that the peak power emitted by 3G cellular phones is much lower (maximum 1 W) compared to the corresponding value issued by the 2G phones. Also, the power will be faded away quickly when the distance increases. These were the reasons for less number of EMI incidents reported via 3G cellular phones compared to the 2G phones. In particular, the studies by Tang et al. [54] and Van Lieshout et al. [87] proved that the possibility of interference of 3G cellular phones with medical devices is considerably lower than that of the 2G phones. These researches have paved the way for the utilization of 3G cellular phones for efficient transmission of voice and data in the healthcare sector.

Modern wireless technologies such as WCDMA and UMTS have similarly been tested with medical devices for their possibility of interfering with medical devices. However, studies have proved that they interfered with a fewer number of devices at closer distances; also, the severity of the interference is not as much as those of the 2G cellular phones. Other technologies, such as the PHS technology that is used in Japan, TDMA phones, and two-way radios used in some countries, were also tested with both critical and non-critical care devices. TDMA, PHS, and two-way radio devices had negligible interference with medical devices and proved to be worthwhile in various healthcare purposes. In contrast, the tested GPRS signal has caused a higher number of devices to be affected than the signals transmitted by voice [87].

Table 1 Summary of the undertaken studies on the EMI in medical devices from the 2G/3G/4G cellular phones.

Reference	Year	Type of study	Cellular system	Number of experienced devices	Number of affected devices	List of affected devices
Hanada et al. [81]	2000	Ad hoc test	PHS system 1.9 G*Hz*	25	Nil	Nil
Karczmarewicz et al. [82]	2001	Ad hoc test	GSM 900 M*Hz*	4 – AED	Nil	Nil
Tri et al. [64]	2001	Ad hoc test	GSM 900 M*Hz*, CDMA, TDMA, and Analogue	17 – Cardiopulmonary devices	7	Cardiopulmonary devices
Shaw et al. [84]	2004	Ad hoc test	GSM 900 M*Hz*	14 – Ventilators	6	Ventilators
Jones and Conway [85]	2005	Ad hoc test	GSM 900 M*Hz*, and two-way radio	5 – Ventilators	1 – GSM 900 M*Hz*, and 1 – two-way radio	Ventilators
Trigano et al. [20]	2005	Case study	GSM 900 M*Hz*	158 – Pacemakers	5	Unprotected model of pacemakers
Trigano et al. [83]	2006	Ad hoc test	GSM 900 M*Hz*, and PCS1800 M*Hz*	3 – Automatic external defibrillators	1 – GSM 900 M*Hz*	AED
Van Lieshout et al. [87]	2007	Ad hoc test	GPRS, and UMTS	61 – Multiple devices	25 – GPRS1, 15 – GPRS2, and 8 – UMTS	Multiple devices
Dang et al. [86]	2007	Ad hoc test	GSM 900 M*Hz*, TDMA and two-way radio	7 – Ventilators	7 – two-way radio, and 1 – GSM 900 M*Hz*	Ventilators
Hans and Kapadia [88]	2008	Ad hoc test	GSM 900 M*Hz*, and CDMA	3 – Multiple devices	1 – GSM 900 M*Hz*	Infusion pump
Calcagnini et al. [98]	2008	Ad hoc test	GSM, DECT, and Wi-Fi	18 – Infusion Pumps	1 – Wi-Fi	Infusion pump
Fung et al. [73]	2009	Ad hoc test	PCS	Multiple devices	2	CO_2 airway adapter and haemo-glucostix meter
Iskra et al. [89]	2009	Bench test	GSM 900/1800 M*Hz*, WCDMA and 80 % AM 1 k*Hz*	14 – Multiple devices	8 – GSM 900 M*Hz*, 1 – WCDMA 9 – 80% AM 1 k*Hz*	Critical care devices
Tang et al. [54]	2010	Ad hoc test	2G, 3G, and PCS	532 – Multiple devices	9 – 2G, 1 – 3G, 8 – PCS	Critical care devices
Ismail et al. [95]	2010	Case study	3G	100 Pacemakers	Nil	Nil
Barutcu et al. [105]	2011	Case study	3G	Cardiovascular devices	Nil	Nil
Helhel et al. [90]	2011	Ad hoc test	2G and 3G	16 – Critical care devices	4 – 2G and 3 – 3G	Critical care devices
Hatara et al. [91]	2014	Ad hoc test	3G, LTE and Half-wave dipole	32 – Critical care devices	12 – Devices altogether by all phones	Critical care devices
Salceanu et al. [92]	2015	Ad hoc test	3G and Microwave oven	One neonatal ventilator	One neonatal ventilator by 3G	Neonatal ventilator
Periyasamy and Dhanasekaran [94]	2015	Ad hoc test	GSM 900 M*Hz* (2G), and 2100 M*Hz* (3G)	10 – Critical care and monitoring devices	4 – 2G, and 4 – 3G	Monitoring devices
Hurstel et al. [106]	2015	3G	Bench test	Electronic Apex Locator	Nil	Nil
Sidhu et al. [107]	2015	3G	Bench test	Electronic Apex Locator	Nil	Nil
Burri et al. [96]	2016	4G LTE	Case study	49 – Implantable cardioverter defibrillators	Nil	Nil

As far as the EMI incidents are concerned, in most of the studies, they were observed in less than one meter from the source of transmission (wireless device) and more devices have exhibited complete EM immunity even at 0 cm distance. Rarely, some incidents occurred at more than one meter. So, as a precautionary measure, it is advisable to use cellular phones and other wireless transmitters at greater than the one-meter distance to prevent the occurrence of EMI incidents.

Conclusions

Based on the literature, it was realized that during the initial development of cellular phones, the 2G cellular phones had caused more interference in the functioning of some medical devices. This has been observed because the medical devices were not originally designed to interact with cell phones on their first come on the scene. By instant, it is the same way that the aircraft was not originally planned that passengers might use an RF emitting equipment onboard. At present, the situation has changed a lot, and the current medical devices are designed to operate safely under any conditions of usage. Maybe the situation is different in some developing countries, where a lot of older equipment may still be in use, and the immunity levels of locally constructed equipment may not be sufficiently high.

Reports of interference with medical devices a decade or more ago have little relevance to the present day, since immunity standards and cell phone technologies have both changed significantly. Anecdotal reports of problems or results of ad hoc testing show that a problem might occur. That is unrelated to the likelihood that an adverse event will occur. Since the prevalence of cell phones is very high and the prevalence of injury to patients from interference from cell phones is very low or possibly zero, the risk (probability) of problems is clearly very low. In the context of medical devices, ''interference'' means any change in operation, but that is not to say that the change is detrimental to the patient. For example, noise on a stored waveform in an ICD counts as ''interference'' even though the patient may not have noticed any effect on the device and the device continued to operate safely. But for sure some level of caution is still needed. Finally, there is no systematic collection of data that allows a comprehensive analysis of risk (likelihood of adverse events from cell phones in ordinary use in hospitals). There does not appear to be cause for concern due to the negative studies, and generally, you have to put a cell phone very close to a device to cause interference (which may or may not pose a safety risk). But a careful analysis would require statistics on the frequency of adverse events across the healthcare system, which apparently do not exist.

Conflict of Interest

The authors declare no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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