Published in final edited form as:

IEEE Electromagn Compat Mag. 2015 ; 4(4): 66–77. doi:10.1109/MEMC.2015.7407182.

RF Interference in Hearing Aids from Cellphones Part 2: Comparing in-use RF coupling to predictions

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Abstract

Cellphones and hearing aids are presently tested for their near-field RF emissions and RF immunity, respectively, to predict their mutual compatibility when used together. In the concluding part of this two-part series, we examine the relationship between these independent device measurements and the resultant in-use coupled RF interference, which may be heard as audio frequency noises by the hearing aid wearer. The established standards are seen to be generally reasonable in meeting the compatibility goals (i.e., ensuring a low level of perceived audio interference), but the combined effects of the relative device positioning, the hand, and especially the head add a high degree of uncertainty to the relationship between the actual in-use RF interference coupling and predictions based on individual emissions and immunity measurements.

Index Terms

electromagnetic compatibility testing; cellular phones; hearing aids; near-field emissions testing; RF immunity testing

I. Introduction and Background

Due to their small size and self-containment, hearing aids experienced many years free from any serious problems with radio frequency interference (RFI). This fortuitous circumstance changed almost overnight with the introduction of digital cellphones in the 1990's. The envelope of the RF pulses in these new digital transmission protocols elicited very significant audio frequency interference from the hearing aids of the day. The square-law detection mechanism inherent in various semiconductor junctions within a hearing aid can convert any audio frequency amplitude modulation (AM) present in the RF signal to audio frequency signals.

As discussed in part 1 [1] of this two-part series, ANSI C63.19 [2] has been developed to better quantify both the propensity of wireless devices generally, and cellphones in particular, to induce RFI, and the susceptibility of hearing aids (HAs) to RFI. An earlier related paper [3] examined the measurement of HA immunity and proposed an improved

GTEM (gigahertz transverse electromagnetic) cell-based methodology. Part 1 of this series took a closer look at the near-field wireless device scan technique specified in ANSI C63.19 and the effect of hands holding a cellphone on those measurements. It proposed a simplified metric for the characterization of the cellphone near-field strength based on a simple average over the defined $5\text{cm} \times 5\text{cm}$ scan area centered 15 mm over the cellphone's acoustic output, and characterized the relatively minor shifts in categorization that would result from its adoption in comparison to the standard's present exclusion area metric. In part 2, we take a detailed look at the ability of these independent emissions and immunity measurements to predict the level of interference that a HA user can expect to experience. It is evident that the hand, the head, and the relative positioning of the cellphone and the HA will all have very significant effects on the actual coupled RFI.

A. Wireless Device Rating

We will be using the full-scan area average established in Part 1 to characterize the cellphone near-field emissions, but we should expand on another important aspect of audio interference-generating potential addressed by the latest revision of C63.19 and touched on briefly in Part 1. The wireless device near-field emission level used by the standard for categorization is not taken from a direct measurement of, for example, peak or rms field strength, neither of which takes into account the signal's audio frequency AM envelope characteristic. Rather, the rated level is derived from the subjectively weighted audio frequency output of a square law detector, simulating the detection processes occurring within a HA and, in a general sense, the user's HA-corrected hearing. The HA user-specific subjective weighting function was developed and defined in [4], and includes both temporal and spectral components. The final measurement, then, takes into account both the overall level of the near-field emissions and the audio frequency interference potential of the emissions' AM characteristic. The resulting quantity is termed "radio-frequency audio interference level" and is defined as, "The level of an unmodulated RF carrier that, when modulated by 80% 1 kHz sine-wave amplitude modulation (AM), produces the same output from a weighted square-law detector as does the modulated RF signal under test when measured with the same weighted square-law detector." This definition relates the subjectively weighted emissions measurement to the HA immunity measurement methodology. In practice, the RF audio interference level is not typically measured directly, but rather the steady state rms emissions level is measured, and a "modulation interference factor" (MIF) applied. The MIF is defined as, "For a modulated signal, the difference, in dB, found by subtracting the signal's steady-state level, in dB, from its radio-frequency (RF) audio interference level, in dB." The MIF is dependent only on a signal's AM characteristic and is independent of its overall level. It can be determined through a separate measurement of a radiated or conducted signal.

B. Hearing Aid Rating

C63.19 measures the RF immunity of a HA by observing the level of its 1 kHz acoustic output in response to an 80% 1 kHz sine-wave AM RF field (along with an approximately 14 dB lower 2 kHz byproduct of the square law detection mechanism). Testing is performed over the RF frequency bands presently of primary interest: 800 MHz to 960 MHz and about 1.5 GHz to 2.5 GHz. Through pre- or post-measurement of the acoustic gain of the HA, the

recovered audio interference at the HA output is referred to the HA input as an equivalent acoustic level in dB-SPL (sound pressure level) at the HA microphone that would have produced the same acoustic output level from the aid, referred to as an “input-referred interference level” (IRIL). The reported RF field strength for the immunity rating of the HA is the field strength level of the unmodulated carrier (calibrated with the hearing aid not present) that, with the modulation added, produces a HA IRIL of 55 dB-SPL at the worst-case frequency in the tested frequency bands. A subjectively perceived audio interference level of 55 dB-SPL results in a speech-to-interference ratio of 25 dB when compared to the standard’s assumed cellphone-produced speech level of 80 dB-SPL at the HA microphone, which the majority of HA users will find acceptable for “normal use” [2].

C63.19 allows for testing the HA immunity either in the near-field of a tuned dipole antenna or in the plane wave approximation established within a gigahertz transverse electromagnetic (GTEM) cell. In both cases, the goal is to determine the immunity at the orientation of maximum sensitivity. The earlier related paper [3] examined GTEM cell HA testing and proposed a new 6 or 12-orientation measurement “maximal sum” procedure to better approximate the true worst-case orientation result. More recently, the method has undergone additional supportive testing [5, 6]. The approach is presently under consideration within the relevant IEC and ANSI committees as a possible common approach to GTEM-based HA RF immunity testing.

C. Predicting Combined Interference

C63.19 rates a cellphone’s RF audio interference level on a decibel scale categorized from M1 to M4, where M4 represents the lowest level of audio frequency RFI-inducing near-field emissions. HA RF immunity is rated on a similar scale, where M4 represents the highest RF immunity. The resultant qualification thresholds are based on a “system performance classification”, wherein the M-ratings of the cellphone and HA are summed. A sum of 4 is considered “usable”, a sum of 5 to be acceptable for “normal use”, and a sum of 6 or greater to give “excellent performance”. Implicit in this summation is some assumption of the relationship between the respective emission and immunity measurements and the effective in-use RF coupling of the cellphone and HA as it pertains to audible interference generation.

A HA immunity rating can, at least conceptually, be mated with a cellphone RF audio interference level rating to predict the subjective interference level that a HA user can expect from a given cellphone/HA combination. This relationship can be expressed by a simple equation:

$$\text{subjectively weighted IRIL} = 2 \times (\text{emissions} - \text{immunity}) + 55 \quad [1]$$

Where:

IRIL = HA input-referred interference level, in dB-SPL

emissions = measured cellphone weighted near-field E or H-field emissions, in dB(V/m) or dB(A/m)

immunity = measured HA E or H-field immunity for 55 dB-SPL IRIL, in dB(V/m) or dB(A/m)

The factor of 2 in the equation results from the square-law detection mechanisms in the HA, where a 1 dB change in RF coupling results in a 2 dB change in recovered audio level.

It is immediately clear that this simple expression glosses over several important considerations pertaining to actual use. Several of these could be accounted for with the incorporation of additional test data specific to given in-use situations. For example, transmit power levels lower than the full power level employed during cellphone testing and more in line with typical use could be considered. HA immunity could be considered at the actual-use condition transmit frequency rather than just at the HA's rated worst-case test frequency. Likewise, the cellphone emissions could be evaluated at the actual-use condition transmit frequency in addition to the standard test frequencies.

An additional significant variable that is not readily ascertainable and which is the topic of this paper is the actual RF coupling experienced in any given use situation relative to what would be predicted from independent, but matched, cellphone emissions and HA immunity measurements. We should expect that the particular relative positioning of the cellphone and HA, and the presence of a hand and a head would all have significant effects on the actual in-use RF coupling. Prior studies [7, 8] examined particular cellphone antenna structures and their interaction with the head and ear canal using numerical modeling. For this study, we measured directly the effective RF coupling between various types of cellphones and HAs in several test conditions to better quantify the range of real-world coupling that can be expected and the contributing factors to that range. We employed eight GSM [9] cellphones of various configurations and eight HAs, and tested in both the low and high cellphone frequency bands. As described in Part 1 of this series, the cellphones consisted of three conventional "candy bar" style, two PDA (personal digital assistant) style, two "slider" style, and one clamshell style. More recent "smartphones" were not yet in wide use at the initiation of the study. The HAs included four behind-the-ear (BTE) aids and four in-the-ear (ITE) aids. We conducted tests with and without hands and with and without an RF phantom head to better identify the contributions of each variable. Not surprisingly, we saw large variations due to the presence or absence of these factors, but identifiable ranges and patterns did emerge.

Testing was carried out at the facilities of the Center for Devices and Radiological Health of the United States Food and Drug Administration, Silver Spring, Maryland and at Gallaudet University, Technology Access Program, Washington, D.C.

II. Test Methodology

The RF audio interference level evaluation method of C63.19 and its associated MIF successfully account for the differing audio interference effects of the AM characteristics associated with various possible modulation protocols. This coupling study could be conducted with just a single modulation characteristic without limiting its general applicability. Further, the study's goals could be accomplished more straightforwardly if the immunity measurements were made using essentially the same AM characteristic as the

cellphone emissions. As long as the HA test configuration remained unchanged for both the immunity tests and the later tests when the HAs were exposed to the cellphone fields, further characterization of the HA output measurement link or the HA's acoustic transfer function would be unnecessary. The predictive accuracy of Equation 1 could be examined without the need for IRIL calculations or their associated acoustic measurements. The obvious choice for a modulation protocol was GSM, as it provided a steady, repetitive pulsed AM characteristic that could be readily approximated by a standard RF signal generator for conducting the HA immunity tests.

As discussed in Part 1, the selection of RF test frequencies was determined by the need to characterize cellphone emissions and the HA immunity at the same carrier frequencies, preferably including both the low and high cellphone bands. The selected frequencies enabled clear interference responses from the HAs at specific GSM channels. Two BTE aids were tested at 890.2 MHz and two at 1850.2 MHz. Three ITE aids were tested at 1784.8 MHz and a fourth ITE aid at both 890.2 MHz and 1850.2 MHz, yielding a total of nine HA immunity test conditions. All eight cellphones were tested at all three frequencies.

A. Cellphone Near-Field Emission Tests

Our cellphone emissions reference was taken as the simple average of the 121-point E-field or H-field scan values over a $5\text{ cm} \times 5\text{ cm}$ grid in a plane centered 15 mm over the acoustic output of the cellphone (0.5 cm step spacing), except where noted. Although the latest revision of C63.19 requires only E-field scanning, we made both E and H-field scans to enable comparisons based on assumptions of either E or H-field-dominant coupling. The E-field results from the average were typically 2 to 3 dB lower than the calculated C63.19-defined exclusion area methodology results.

We repeated all the scans at the 15 mm height with the phones held by “small” (subject K) and “large” (subject J) hands, both left and right, with normal grip positions stabilized with the help of a guide grid and spacers. These grip positions were substantially the same as employed later for combined cellphone/HA testing with an RF phantom head. In comparison to the Cellular Telephone Industry Association-specified phantom hand phantom dimensions [10], subject K's hands were smaller in each of the six specified linear dimensions by 2% to 14%, while subject J's hands were larger in each dimension by 4% to 23%. The grips employed also differed between the two subjects, with subject K employing a light, fingertip grip and subject J a closer, more encompassing grip.

We anticipated that it would be necessary to reduce the cellphone power during some of the combined cellphone/HA tests to avoid HA overload. We checked the nominal 2 dB power step linearity for each phone at each frequency by relative measurements of the radiated field for later input into our data analysis.

B. Hearing Aid RF Immunity Tests

As discussed in the earlier related paper [3], determining the HA immunity at its most sensitive orientation to an RF field establishes a consistent upper bound on HA RF sensitivity. The preferred immunity test method of C63.19 searches for that orientation with the HA placed in the near-field of a tuned dipole antenna, both over the center of the dipole,

where the H-field is highest and over a tip, where the E-field is highest. An alternate method in the standard places the HA in the plane wave approximation of a GTEM cell in various orientations. The IEC 60118-13 [11] HA immunity test is similar to this alternate method, but uses different HA rotations within the GTEM cell. We performed dipole-based tests essentially as specified (except for the excitation signal). For GTEM-based tests, we employed the six-orientation “maximal sum” method [3] to obtain the closest approximation to the maximum sensitivity orientation result.

For both immunity tests, we used a simulated GSM pulse train for the excitation signal, rather than the 80%, 1 kHz AM specified in the ANSI and IEC standards. This consisted of 576 μs pulses repeating every 4.615 msec (pulse repetition rate of 216.7 Hz), generated by an Agilent model E4432B signal generator feeding low band or high band power amplifiers, as required. The burst field strengths at the hearing aid location ranged from 5.4 V/m to 240 V/m in the GTEM, and 18 V/m to 1,100 V/m and 0.081 A/m to 3.1 A/m at the dipole calibration points. The wide field strength ranges were needed to ensure clean, noise-free measurements without HA overload for the variety of HAs employed. Dipole and GTEM calibrations were performed using CW signals set to the same amplitude as the simulated GSM pulses.

For both the immunity tests and the later combined cellphone/HA tests, the recovered audio at the acoustic output of the HA was channeled through five meters of 4 mm inside diameter silicone tubing to a custom-built, switchable gain microphone/amplifier combination. The output fed a fixed-gain 16-bit analog-to-USB converter, which in turn fed a laptop computer. Extremely narrowband filtering of the recovered audio enhanced the rejection of measurement noise. The processing software (Adobe Audition) selected the 4th harmonic (867 Hz) of the detected pulse stream while rejecting noise outside a ± 4 Hz bandwidth around that frequency. The selected harmonic is in the mid-audio frequency range for the HA and exhibits an amplitude almost as strong as the fundamental. We insured that the HAs were operating in their linear mode, with no level compression or active processing, and did not clip. They therefore were operating in their accurate square law detection range (i.e., a 1 dB change in the RF exposure level results in a 2 dB change in recovered audio).

C. Tuned Dipole Near-Field Immunity Tests

ANSI C63.19 specifies the use of two resonant dipole antennas as near-field RF sources, one for the cellphone low band frequencies (800 MHz – 950 MHz) and one for the cellphone high band frequencies (1.6 GHz – 2.5 GHz). The field is calibrated 15 mm above the surface of the dipole: above the dipole center for H-field calibration and above a tip for E-field calibration. Figs. 1a and 1b plot measured field strengths at the 15 mm height along the length of low band and high band dipoles, respectively, with 100 mW drive. We further calibrated the antenna fields at our specific test frequencies. With the aid of RF-transparent spacers to maintain the 15 mm distance between the dipole and the nearest surface of the HA, the HA is rotated in all possible orientations until the maximum sensitivity to the modulated RF field is found.

We performed the search for the maximum-sensitivity orientation by hand, controlling the HA positioning through the attached tubing. We then secured the HA in position using a

plastic supporting stand, as can be seen in the photos of Figs. 2a and 2b. To ensure that we had discovered the maximum sensitivity positioning in each case, three different testers repeated the tests on consecutive days without direct reference to the previously chosen orientations, but recording the positions photographically. In general, agreement between the testers was good. However, when the difference in results between testers was more than two dB, the weaker test was repeated, this time matching the recorded HA positioning of a stronger result. A good match was then able to be achieved between at least two of the three testers. Each final result was taken as the average of the two or three highest and now closely matching results.

D. GTEM Immunity Tests

The six-orientation maximal sum methodology [3] employed provides a close approximation to the HA immunity at its most sensitive orientation in the GTEM field. This method is essentially a variant on prior sorted three-input vector summation methods that effectively finds the maximum of all 32 unique orthogonal sums derived from 90° rotations of a bounding cube aligned with the applied plane wave.

For our testing, the use of a fixture consisting of an actual cube constructed of ¼" diameter rods of very low loss Rexolite™ plastic resting on an expanded foam base provided for consistent positioning of the HA's required six orientations within the large EMCO model 5317 GTEM cell shown in Fig. 3 (maximum septum height of 175 cm). To enable strong field levels, we placed the HAs far forward in the cell, where the septum height was 34.6 cm. We positioned the HAs midway between the septum and the GTEM floor, aligning the cube dimensions so as to make equal angles with each of the opposing surfaces. A check with a 3-axis field probe (Amplifier Research FP2083) confirmed that this positioning very closely aligned the vertical dimension of the cube with the E-field vector at the test location.

As with the dipole immunity tests, forward power was monitored through a bidirectional coupler, which allowed for compensation of minor power amplifier gain drifts due to self-heating. Field levels in the GTEM were monitored, but these closely corresponded to the ideal theoretical field strengths given by:

$$E = \sqrt{P_{in} * Z_0 / h} \quad [2]$$

where:

E is the electric field strength (V/m)

P_{in} is the input power to the GTEM (Watts)

Z_0 is the characteristic impedance of the GTEM cell (50 Ohms)

h is the septum height at the test location (0.346 m)

Because the field probe readings and theoretical field strength values were in close agreement, we used the calculations referenced to the input forward power to record E-field strength.

E. HA RF-Immunity Test Comparisons

The GTEM immunity test employed does not differentiate between E-field and H-field sensitivity. The HA is exposed to the fields in their free-space ratio of 377 Ohms, but leaves undiscovered the degree to which each field component contributes to the HA's RF pickup. When employing GTEM E or H-field immunity data in the following analyses, it will be assumed that the reported E or H-field values represent the dominant contributors. In contrast, the dipole test does separate E and H-field sensitivities to some degree.

Fig. 4 compares the sensitivities to E and H-fields of the aids as measured by the dipole method to the sensitivities as implied by the GTEM method. The large differences between the two methods have been reported in several prior studies, most recently in [12] and [13]. Presumably, the apparently greater immunity implied by the dipole tests results from a lower actual field strength exciting the HA's incidental receiving structures relative to the field strength calibrations, in comparison to the corresponding relationship in the GTEM tests. The present ANSI C63.19 revision recognizes this typical measurement difference and offsets the respective qualification levels by 7 dB between its dipole and GTEM methods. We will make use of both sets of results to see if one method is more consistently predictive of in-use coupling than the other.

III. Combined Cellphone – Hearing Aid Interference Tests

Equation 1 gave a coupled interference prediction based on measures of cellphone RF emissions and HA RF immunity that can be compared against actual measured paired coupling. As noted, this comparison can be made without taking the additional steps needed to calculate HA IRIL by maintaining the same acoustical measurement setup when initially measuring HA immunity and then again when measuring the paired coupling. For our purposes, Equation 1 can be modified according to Equation 3:

$$\text{predicted audio} = 2 \times (8.96 + \text{emissions} - \text{immunity}) + \text{measured audio} \quad [3]$$

Where:

predicted audio = HA 4th harmonic (867 Hz) sound pressure level from cellphone excitation, in dB(SPL)

emissions = cellphone near-field E or H-field RF emissions, rms level in dB(V/m) or dB(A/m)

immunity = HA E or H-field immunity test RF excitation burst level, in dB(V/m) or dB(A/m)

measured audio = HA 4th harmonic (867 Hz) sound pressure level at the test RF excitation burst level, in dB(SPL)

In contrast to its usage in Equation 1, “emissions” as used here is simply the long-term-averaged rms level without the addition of the MIF, as would have been required to determine the M-rating in C63.19. “Immunity” here is simply the burst level of the applied pulse stream that elicited the “measured audio”. These clarifications mostly explain

appearance of 8.96 dB in Equation 3. Additionally, the actual cellphone GSM signals differed from the pure 1/8 duty cycle pulse train employed for the immunity tests in that, as controlled by the base station simulator, the transmitted steady-state GSM signal was continuous except for missing every 26th pulse. Also, due to the finite rise and fall times of the GSM pulses, a better duty cycle approximation could be taken as about 1/8.2, instead of 1/8. These elements combine to imply a GSM signal burst level 9.31 dB higher than the measured long-term rms level. The selected 4th harmonic of this GSM signal at 867 Hz is, by Fourier analysis, 0.35 dB lower than that of the HA test signal pulse train at the same burst level. Taking all these individual factors into account arrives at the net correction factor of 8.96 dB. We should emphasize that these considerations do not apply when testing according to ANSI C63.19, as the relationship between the cellphone emissions measurement and the HA immunity measurement is established through the MIF and the RF audio interference level.

We will be comparing the predicted audio of Equation 3 to the actual audio interference measured with a cellphone held by a hand in its normal-use position against a hearing aid in position on an RF phantom head. We will build up to this final, normal-use comparison in stages, though, in order to gain some insight into the influences of the various factors affecting the coupling. The first comparison to be examined will be an attempt to create the best possible match between prediction and measured coupling by ignoring the limitation of normal-use relative positioning and the presence of a hand and head. Next, typical normal-use relative positioning will be established between the cellphone and HA, but still without a hand or head. This normal-use positioning will then be moved to the phantom head, still without a hand, and then finally the hand added. Comparisons along the way will shed light on which factors contribute the most variability and how well the emissions and immunity-based coupling predictions hold up. In these comparisons, the difference between the predicted audio interference and the actual measured audio interference is divided by two, taking into account the square law detection mechanism, to represent the predictive error in effective RF coupling.

A. Maximum Coupling Positioning – No Hand or Head

It may be surmised that the best correlation between prediction and actual coupling may be found by placing the HA over the cellphone E or H-field maximum within the scanned area with no hands present and searching for the strongest coupling orientation relative to the field at that location (in this instance, basing the coupling prediction on the maximum measured cellphone E or H-field, not the scan area average). For these tests, small Rexolite™ spacers maintained minimum distances of 5, 10, or 15 mm between the cellphone and the closest point on the HA while the maximum coupling search was performed manually. The HA was then secured in position with the holding fixture, as shown in Fig. 5. The 15 mm distance corresponds to the calibration spacing used in the dipole immunity testing, but the closer distances correspond to what we established would be practical in-use separations between the cellphone's acoustic opening and the HA's microphone when mounted on the phantom head: 5mm for an ITE HA and 7.5 mm for a BTE HA. The differences between the net coupled interference at the three distances were

small and similar to the minor field strength differences at the three scan heights of 10mm, 15mm, and 20mm plotted in Fig. 3 of Part 1.

Based on the 5mm spacing data, Fig. 6 compares this measured coupling to four possible coupling predictions based on the combination of the cellphone E or H-field maximum at a 15mm scan height and the corresponding E or H-field HA immunity as determined by dipole or GTEM tests, and assuming E or H-field coupling. As will also be included in subsequent graphs, the mean, standard deviation, and overall range of each condition are indicated. No clearly best predictor emerges from this comparison. Combining the emissions maximum with the dipole-based immunity measurement tends to under-predict the actual coupling, while utilizing the GTEM-based immunity measurement tends to over-predict the actual coupling.

B. Normal-Use Relative Positioning – No Head or Hand

The next step taken was to place the HA in its normal-use positioning relative to the cellphone as if both were in place on a head, but without a hand or head present, as illustrated in Fig. 7. A 7.5 mm spacer for the BTE aids and a 5 mm spacer for the ITE aids kept them at typical in-use distances from the cellphone. The BTE aids were tested in both left ear and right ear configurations, while the ITE aids were tested only as if worn in their intended ear. Fig. 8 shows the general reduction in coupling in going from the previous maximum coupling positioning (at the E or H-field maximum location) to this normal-use relative positioning.

These large coupling changes, along with the drastic changes in the cellphone near-field that adding a hand can induce, further reinforce the notion that basing in-use cellphone interference predictions on a narrow parameter such as the scan maximum or the present C63.19 exclusion area methodology does not imply greater predictive consistency than would a simpler, broader emissions measure. The 121-point no-hand scan average over the full 5 cm × 5 cm scan area (15 mm scan height) will be used for further predictive comparisons.

Fig. 9 compares the measured coupling with this normal-use relative positioning of the cellphone and HA (still with no hand or head) to predictions based on this broader no-hand cellphone emissions metric. The coupling predictions based on the dipole-based HA immunity measurements average somewhat closer to the measured coupling, but, allowing for a predictive offset resulting from the typical 7 dB difference between the two immunity measurement methods, there is still no clearly most-consistent predictor among the four emissions – immunity measurement pairings.

C. Normal-Use Positioning – Phantom Head, No Hand

A further step places the cellphone and HA in their normal-use positions on a head, but still with no hand. For these tests, the cellphones were held in place on the RF phantom head by a thin, nonmetallic strap and a 5 mm or 7.5 mm spacer for the ITE or BTE aids, respectively, as shown in Fig. 10. The phantom head was made by MCL-T using a carbon-loaded silicone material [14], and incorporated acoustic porting from the ear canals. Comparative acoustic measurements were made on each ITE aid when mounted in the head to enable

compensation for the changed acoustic path through the added tubing length. As with the previous test condition, the ITE aids were tested in their appropriate left or right ear, while the BTE aids were tested on both sides.

Very wide ranges in predictive accuracy were observed relative to each of the four predictive emissions – immunity measurement pairings studied. Fig. 11 plots the ranges of predictive differences for the eight cellphones for each of the HAs taken individually, based on assumed E-field coupling and GTEM immunity measurements. The corresponding graphs for the other three parameter pairings are very similar, allowing for the 7 dB typical GTEM vs. dipole immunity measurement difference. The ITE aids, which are partially inserted into the ear canal, showed much more variation than the BTE aids.

D. Normal-Use Positioning – Phantom Head, With Hand

The final step to a realistic use condition is to keep the phone and HA in their normal-use positions on the head, but now held by a hand, as shown in Figs. 12a and 12b. The plot of Fig. 13 shows that holding the phone in the normal-use position can increase or decrease the coupling compared to the same position without the hand, but on average, reduces the coupling 5 dB. Interestingly, in spite of the large differences due to hand size and grip of subjects J and K seen in Part 1 in the with-hand emissions scans taken without a head [1, Fig. 9], there is surprisingly little difference seen here between the effects of the two subjects' hands with the phantom head present.

Similarly to Fig. 11, but now with both the head and subject J's hand present, Fig. 14 plots the ranges of predictive differences for the eight cellphones for each of the HAs taken individually, again based on assumed E-field coupling and GTEM immunity measurements. The corresponding graphs for the other three parameter pairings and subject K's hands are very similar, allowing for the small hand difference seen in Fig. 13 and the 7 dB typical GTEM vs. dipole immunity measurement difference. This data is very similar to and just a few decibels lower generally than that of Fig. 11, which shows the same comparisons without a hand.

Considering the wide ranges in effective coupling compared to prediction illustrated in Fig. 14, it might be reasonable to ask how closely related the final coupled interference is to the measured differences in cellphone emissions. Fig. 15 plots the measured with-head, with-hand coupled interference (in terms of coupled RF, not recovered audio level) for 208 combinations of cellphone, HA, and subject hand vs. the measured 121-point average E-field emissions (no hand or head) of the exciting cellphone. To enable a common basis for comparison, each data point is normalized to the predicted average coupling for all 8 phones for that HA. If the actual coupled interference were to correlate closely with the measured emissions, the trend line would exhibit a slope of 1, with the data points close to this line. Instead, the trend line shows little slope and the data points are widely scattered.

IV. Conclusions

Our goal with this study has been to characterize the relationship between near-field measures of cellphone RF emissions, measures of HA RF immunity, and the range of RF

coupling that results when cellphones are used with hearing aids. We have examined various candidate measurement methods for both cellphone near-field emissions and HA immunity. We have observed the effective RFI coupling under various conditions in order to better understand the significant emissions and immunity measurement parameters and their ability to predict in-use interference. From the resultant data, we can draw several conclusions and recommendations:

- Whether E-field coupling or H-field coupling dominates in a given scenario or whether the fields contribute roughly equally is difficult to determine in practice. Coupling predictions based on either assumption did not differ materially from each other, whether using GTEM-based or dipole-based HA immunity measures. This result tends to validate the decision made in the latest revision of ANSI C63.19 (2011) to measure only cellphone E-field emissions and not H-field emissions.
- Similarly, coupling predictions based on either GTEM-based or dipole-based HA immunity measurements did not differ materially in their predictive consistency, as represented by means, standard deviations and overall ranges. Our data were consistent with a previously observed 7 dB typical offset between the two measurement methods. We do believe that a GTEM-based method using the six-orientation maximal sum methodology is to be recommended, as it provides a consistently close approximation to the HA's immunity at its most sensitive orientation to the field at each tested frequency through a straightforward, prescribed procedure. In contrast, the dipole-based method requires an effectively ad hoc search procedure to find the most sensitive orientation that does not ensure consistent results and is not practical to repeat at each test frequency. It does not yield improved predictive consistency that would compensate for its difficulties.
- Holding a cellphone changes the magnitude and distribution of its near-field dramatically, as does the presence of a head. A complicated near-field metric such as the present exclusion area calculation of C63.19 loses its relevance in actual use. In Part 1, we recommended a simpler metric such as the average over the 5 cm × 5 cm square centered 15 mm above the cellphone's acoustic output.
- Coupling predictions based on assumed E-field coupling, a 5 cm × 5 cm square cellphone near-field emissions scan average, and a six-orientation maximal sum GTEM-based HA immunity test provide a generally conservative estimate (overestimation) of actual in-use coupling by about 0 to 30 dB, with the very notable exception in these tests of one ITE HA, which exhibited about 20 dB more in-use coupling relative to prediction than the others. The differences between predicted and actual in-use coupling varied more among the various hearing aids, particularly the ITE aids, than among the eight cellphones tested. The differences between the two subjects' very different hand sizes and grips essentially disappeared in the normal-use, on-the-phantom head tests.
- The overall range of measured cellphone near-field emissions levels of the eight tested phones of about 8 dB in each frequency band is actually fairly modest in

comparison to other variables contributing to the final level of in-use coupled interference. Specifically, the relationship of the normal-use coupling to the predictions based on the emissions and immunity measurements varies over a much wider range. It may be surmised that, in comparison to this wide range, the interference-generating near-field emissions of various cellphones operating within the same protocol and power levels will likely not show large variations in their interference-producing abilities. Larger variations in cellphone audio interference-generating potential can be expected from protocols having differing MIFs and wireless devices having differing power levels. In particular, the MIF can vary from +3.3 dB for GSM modulation to perhaps -20 dB for protocols exhibiting very low levels of audio-frequency amplitude modulation. ANSI C63.19 presently includes a low-power wireless device testing exemption (not requiring near-field emissions scanning) that combines a wireless device's MIF with its maximum average antenna input power, comparing the result against a conservative threshold. An implication of our results is that these two factors taken together could prove to be the most relevant cellphone parameters in predicting interference coupling to a HA and that contributions from the comparatively modest cellphone product-to-product variation within a given protocol are likely minor by comparison.

The final question to address is how these predictive coupling comparisons relate to the wireless device and HA test qualifications established in C63.19. The standard rates both the wireless device emissions level and HA immunity in categories numbered M1 through M4, each 5 dB wide. A sum of the wireless device rating and the HA rating of at least five for a wireless device-HA pairing is expected to provide adequately low RF-induced audio interference for "normal use" – no more than about 55 dB-SPL IRIL. Allowing for the spread of the category windows and considering the typical 2 to 3 dB difference between the exclusion area metric and the simple area average basis of our analysis, we calculate that in order not to exceed a 55 dB-SPL IRIL, the actual coupling should be at least 5 to 15 dB lower than a category sum-based prediction in the low band (<960 MHz) and at most 6 dB higher to at least 4 dB lower in the high band (>960 MHz). (The low band and high band wireless device M-ratings are offset 10 dB from each other in recognition of the higher cellphone E-fields in the low band compared to the high band and the generally greater HA immunity in the low band compared to the high band, although this assumed immunity difference is not presently accounted for in the HA M-rating procedure.)

Looking back at Figure 14, it can be seen that for subject J, with the exception of ITE2, the measured couplings meet the implied requirements in the high band, and mostly, but not entirely in the low band. But other considerations add to the safety margin. While the cellphone emissions scans are taken at a representative mid-band frequency and large differences throughout the band should not be expected, the HA immunity rating is based on the worst-case frequency result across both bands. A HA's immunity can be expected to vary considerably with frequency and so, in use, will most often exhibit better immunity than its rating would indicate – particularly, as noted, in the low band. Also, cellphones seldom operate at their full rated power, which is the basis for their rating.

This study has served to justify and validate cellphone emissions and HA immunity measurement procedures, and established the ranges of their relationship to actual in-use operation. It has further shown that, with consideration for proposed simplifications and improvements in the cellphone emissions and HA immunity measurement methods, the cellphone and HA qualification levels as set forth in ANSI C63.19 are not unreasonable in their correlation to in-use interference potential. However, the relatively modest contribution of the tested cellphone near-field level differences to the wide variations in net coupled in-use interference suggests consideration of a simpler protocol-wide wireless device qualification based on MIF and antenna input power.

Acknowledgments

This work was supported by the National Institute on Disability and Rehabilitation Research, U.S. Department of Education, under grant number H133E080006. The contents of this paper do not necessarily represent the policy of the Department of Education, and you should not assume endorsement by the Federal Government.

The contents of this paper were also developed, in part, with funding from a grant from the Verizon Foundation.

The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health and Human Services.

The authors would like to thank Frank K. Umberger for his hours of help in test equipment setup and maintenance, and responding to our numerous requests for assistance, Gonzalo Mendoza for operation of the robotic scanning equipment and detailed data reporting, Danielle Han for aid in dipole immunity testing and corresponding data consolidation, and Motorola Mobility, Inc. for the generous loan of the head phantom and base station simulator.

References

1. Beard B, Julstrom S, Kozma-Spytek L. RF Interference in Hearing Aids from Cellphones – Part 1: Near-field cellphone emissions measurements and the effects of hands. *IEEE EMC Mag.* 2015; 4:59–66. qtr. 3.
2. Methods of Measurement of Compatibility between Wireless Communications Devices and Hearing Aids. ANSI Standard C63.19. 2011
3. Julstrom S, Kozma-Spytek L, Beard B. Radio Frequency Immunity Testing of Hearing Aids. *IEEE EMC Mag.* 2013; 2:69–87. qtr. 2.
4. Julstrom S, Kozma-Spytek L, Isabelle S. Telecoil-Mode Hearing Aid Compatibility Performance Requirements for Wireless and Cordless Handsets: Magnetic Signal-to-Noise. *J. Am. Acad. Audiol.* Sept.2011 22:528–541. [PubMed: 22031677]
5. Julstrom, S. Maximal Sum Hearing Aid RF Measurement Test Result Overview; presentation to the EHIMA EMC working group; Copenhagen, Denmark. Oct. 2013;
6. Kattenbeck D. Results of Proposal 5, Parts 1, 2, 3. report to EHIMA EMC working group. Apr.2014
7. Skopec M. Hearing aid electromagnetic interference from digital wireless telephones. *IEEE Trans. Rehab. Eng.* Jun.1998 6:235–239.
8. Caputa K, Stuchly MA, Skopec M, Bassen HI, Ruggera P, Kanda M. Evaluation of Electromagnetic Interference from a Cellular Telephone with a Hearing Aid. *IEEE Trans. Microwave Theory and Techniques.* Nov.2000 48(11):2148–2154.
9. Global System for Mobile Communication (GSM). <http://www.gsm.org/>
10. Test Plan for Mobile Station Over the Air Performance, Rev. 3.1. CTIA Certification. Jan.. 2011 <http://www.ctia.org/docs/default-source/default-document-library/ctia-test-plan-for-mobile-station-over-the-air-performance-revision-3-1.pdf?sfvrsn=0>
11. Electroacoustics - Hearing aids - Part 13: Electromagnetic compatibility (EMC). IEC Standard 60118-13. 2011

12. Kristensen, AG. Comparison of IEC 60118-13 and ANSI C63.19 EMC measurements. DELTA Technical-Audiological Lab; Horsholm, Denmark: Jul. 2007 Tech. note A930294
13. Victorian, T. EMI GTEM Dipole Data and Analysis – Delta, Environ and Starkey measurement comparisons; presented at the ANSI C63.19 WG3 meeting; Piscataway, NJ. April 2009;
14. Gabriel C. Tissue equivalent material for hand phantoms. Phys. Med. Biol. 2007; 52(14):4205–4210. [PubMed: 17664603]

Biographies

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Linda K. Kozma-Spytek received the B.S. and the M.A. degrees from Washington University, St. Louis, MO, in 1981 in speech and hearing sciences and in 1989 in communication arts, respectively. She worked at Central Institute for the Deaf from 1981–1988 in education and research. From 1988–1996, she worked as a research associate in the Center for Auditory and Speech Sciences at Gallaudet University. In 1998, she received her certificate of clinical competence in audiology. Since 1998, she has worked in the Technology Access Program at Gallaudet University as a research audiologist. Currently, she is the co-director of the Rehabilitation Engineering Research Center on Technology for Individuals who are Deaf or Hard of Hearing. Her research interests include issues related to

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Stephen D. Julstrom (M'11) studied electrical engineering at the University of Iowa, 1970–1973. He worked at the Univ. of Iowa School of Music Recording Studio, 1978–1981, supervising students, teaching music recording, and designing a laser projection art control system. From 1981–1992, he was an engineer at Shure, Inc., where he designed wired and wireless microphone circuitry, automatic microphone control and teleconference systems, and surround sound encoders and decoders. Since 1993, he has operated as Julstrom Consulting and Development, Chicago, Illinois, providing research and design services in primarily audio and acoustic-related fields. He has contributed to several ANSI and TIA standards, has published papers in engineering and audiology journals, and holds 20 patents. In 2011, he received the President's Award from the Hearing Loss Association of America.

Fig. 1.

Measured E-field (Figure 1a) and H-field (Figure 1b) strengths at the specified 15 mm height along the length of low band and high band tuned dipoles with 100 mW drive at their center frequency; low band dipole in blue and high band dipole in brown. Dotted lines demarcate the physical ends of the dipoles. (Also reproduced in ANSI C63.19 [2].)

(A)

(B)

Fig. 2.

Examples of positioning for maximum response. 2a) An ITE aid in an E-field test using the high-band tuned dipole antenna, and 2b) a BTE aid in an H-field test using the low-band tuned dipole antenna.

Fig. 3.
The large EMCO model 5317 GTEM cell used for hearing aid immunity testing, with the signal generator and forward and reverse power meters in the foreground.

Fig. 4.

Histogram comparing the GTEM-measured implied E and H-field HA sensitivities to the tuned dipole-measured E and H-field sensitivities for the nine HA test conditions.

Fig. 5.

The first coupling test sequence positioned the hearing aid over the E or H-field maximum in its strongest coupling orientation. (The field distribution shown on the printed scan grid used for alignment is not for this particular phone.)

Fig. 6.

Comparing the measured coupling with the hearing aid oriented for the strongest response when positioned over the phone's scanned E or H-field maximum to a prediction based on the individual emissions and GTEM or dipole immunity measurements ($n = 71$ in each category). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 7.

The second coupling test sequence positioned the hearing aid in its normal-use positioning relative to the phone, but without a hand or head.

Fig. 8.

Comparing the coupling with the hearing aid and cellphone in normal-use relative positioning (without a hand or hand) to the coupling at the strongest relative positioning, assuming E or H-field coupling ($n = 102$ in each category). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 9.

Comparing the coupling with the hearing aid and cellphone in normal-use relative positioning (without a hand or hand) to predictions based on the 121-point scan average and either dipole-based or GTEM-based immunity measurements, and assuming E or H-field coupling ($n = 102$ in each category). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 10.
A cellphone and an ITE aid in position on the phantom head without a hand.

Fig. 11.

Comparing the coupling with the hearing aid and cellphone in normal-use positioning on a head, but without a hand, to coupling predictions based on the 121-point emissions scan average, separated by hearing aid (predictions based on GTEM hearing aid immunity measurements and assumed E-field coupling). (n = 16 for each BTE aid; n = 8 for each ITE aid). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 12. Normal-use positioning on the phantom head, held by the small hand of subject K (Figure 12a) and the large hand of subject J (Figure 12b). Low-loss spacers aid positioning of the phone.

Fig. 13.

Comparing the coupling with the phones held by each of the subjects' hands to the same positioning on the head without the hands ($n = 104$ in each category). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 14.

Comparing the coupling in the final on-head, with-hand condition for subject J's hands to coupling predictions based on the 121-point emissions scan average, separated by individual hearing aids (predictions based on GTEM hearing aid immunity measurements and assumed E-field coupling). (n = 16 for each BTE aid; n = 8 for each ITE aid). Means (horizontal red bars), standard deviations (vertical green bars), and overall ranges (vertical blue bars).

Fig. 15.

Scatterplot and trend line of measured with-hand, with-head RF coupling, normalized for each HA to the average predicted coupling for all 8 phones for that HA. (n = 208)