Published in final edited form as:
IEEE Electromagn Compat Mag. 2013 July 2; 2(2): 69–81. doi:10.1109/MEMC.2013.6550935.

Radio Frequency Immunity Testing of Hearing Aids

Stephen D. Julstrom [Member, IEEE],
Julstrom Consulting and Development

Linda K. Kozma-Spytek, and
Gallaudet University

Brian B. Beard
U. S. Food and Drug Administration Center for Devices and Radiological Health

Abstract

For many Equipment Under Test (EUT), such as the hearing aids examined in this study, the desired RF immunity measurement result is that which would be measured in the most sensitive EUT orientation relative to an applied RF field. This is generally approximated from measurements at a number of predetermined orientations within a GTEM cell. This paper presents new 6 and 12-orientation "maximal sum" methods of small EUT immunity measurement, which may be considered extensions to present sorted three-input vector summation techniques. Experimental results for the new methods approached the established reference goal more consistently than did other approaches examined employing a comparable number of contributing measurements.

Index Terms

Electromagnetic compatibility testing; GTEM; hearing aid interference; RF immunity testing

I. Introduction and Background

Over the years, hearing aids and telephones have led a sometimes troubled coexistence. Positioning the telephone earpiece near the hearing aid microphone is sometimes awkward and, due to design constraints of the hearing aid, can lead to squeals of acoustic feedback. Several decades ago, many hearing aids began to incorporate magnetic sensing coils known as "telecoils" that responded to the stray audio frequency magnetic field from the telephone receiver, instead of to its acoustic output. This coupling mode can yield a clearer sound and avoids picking up ambient noises. Its importance led to federal regulations in the U. S. pursuant to the 1988 Hearing Aid Compatibility (HAC) Act (Public Law 100–394) that, among other things, mandated minimum requirements for telephones' magnetic fields. Cell phones, however, were exempt from these HAC requirements. With the advent of widespread cell phone use, the exemption for wireless devices was later partially lifted [1].

As digital cell phones began to replace analog phones in the 1990's, radio frequency interference (RFI) quickly emerged as a major compatibility consideration. The primary RFI concern was then and remains audio-frequency interference related to the amplitude modulation (AM) envelope of the RF field of the wireless device (WD), which can undergo square-law detection by various semiconductor junctions within the hearing aid in both the microphone and the telecoil operating modes. The most interfering WD transmission protocols are those that employ some form of time division multiplexing, where the carrier is repeatedly pulsed on for only a portion of the transmission time. This pulsing typically occurs at repetition rates near or within the audio frequency band. A prime example is GSM [2] modulation, which pulses with a 1/8 duty cycle at a 216.7 Hz repetition rate.

A working group was soon formed within the American National Standards Institute (ANSI) Accredited Standards Committee C63® electromagnetic compatibility committee to develop ANSI C63.19 [3], which addresses the measurement of both wireless device emissions and hearing aid RF immunity. The U. S. Federal Communications Commission references the present version of this standard for use in certifying HAC compliance of wireless devices. Parallel work on hearing aid immunity standards was also undertaken in the development of International Electrotechnical Commission (IEC) 60118-13 [4]. The development of these standards, perhaps not surprisingly, has been an extended process. The early work in this area is reviewed in [5]; with further updating in [6] and [7].

Since the final judgment of interference acceptability is the subjective tolerance of the end user to the resultant audible noise, studies were undertaken to determine the required user-perceived signal (speech) to noise (interference) ratio, as reported in [8], [9], and [10]. A more recent study [11], while specifically addressing telecoil mode interference, looked at a wider variety of more recent interfering noise types (RF modulation characteristics). That study established a new audio frequency subjective weighting function to better enable objective evaluation of the interference potential for hearing aid users of emerging transmission protocols. The weighting function is now incorporated in the wireless device emissions testing methodology of the latest revision of ANSI C63.19.

The evaluation of the interference potential of wireless devices by means of near-field emissions scans and accurate measurement of the RF immunity of hearing aids, combined with a net resultant minimum S/N ratio criterion, established a basis for mutually compatible emissions and immunity standards. The effective in-use RF coupling between a wireless device and a hearing aid is subject to many variables, though, including the relative positioning of the source and receiver, and the effect of the hand and head. The authors are presently involved in a study designed to better understand the effects of these variables and their relationship to predictions based on established emissions and immunity test methods and possible variations on those methods. A significant part of this undertaking has been the desire to establish the most consistent, meaningful, and practical method of evaluating hearing aid RF immunity.

ANSI C63.19-2011 and IEC 60118-13-2011 establish related but differing hearing aid RF immunity test methods and requirements. 60118-13 specifies hearing aid excitation in a GTEM (gigahertz transverse electromagnetic) cell. C63.19 establishes a preferred immunity test that places the hearing aid in the near field of a tuned dipole antenna. Separate tests are conducted near the tip of the dipole and near its center, to elicit primarily E-field and H-field responses, respectively. C63.19 also establishes an alternative immunity test that places the HA in a GTEM cell in a manner similar, but not identical, to the 60118-specified method.

Many studies have been conducted comparing the results of ANSI dipole vs. IEC GTEM testing, with [12] and [13] being the most recent. A general result has been an apparent 5 to 15 dB greater RF immunity using the dipole method in comparison to the GTEM measurements. This oddity may presumably be at least partly ascribed to differences in the actual field strength exciting the hearing aid's incidental receiving structures, as compared to the field strength calibrations. ANSI C63.19-2011 recognizes this difference by offsetting the test requirements 7 dB between its two specified methods. One aspect of the authors' ongoing study is to determine which of the methods results in greater accuracy and consistency in predicting in-use interference.

A consistent complaint regarding the dipole procedure is its greater practical measurement uncertainty and related EUT (Equipment Under Test) positioning difficulties. The test involves rotating the irregularly shaped hearing aid in all orientations to find the most sensitive alignment while maintaining a constant spacing from the nearest EUT surface to the dipole tip or center, typically by using RF-transparent spacers. This is inherently a time-consuming manual, ad hoc procedure. Repeating the orientation search at multiple frequencies over a tested band is impractical. The dipole test does have the advantages of producing high field strengths with ease and of being able to separate out to some degree E vs. H-field sensitivity. Practical testing experience of wireless devices and hearing aids showed, however, that both the WD near-field emissions and the hearing aid immunity ratings exhibited a modest tendency to be dominated by their respective E-field measurements. Potential ratings changes for both WD emissions and HA immunity were seen to be minor if the H-field results were excluded and the ratings based solely on the E-field results [14]. Although the latest ANSI C63.19 revision does maintain the H-field requirement for dipole-based HA immunity testing, it drops the WD H-field emissions test requirement.

In comparison to the dipole-based testing, GTEM-based immunity testing has the advantages of creating a controlled test environment and of straightforward, consistent placement of the EUT within a well-calibrated field. An informal survey conducted by the authors of seven major hearing aid manufacturers and test laboratories in 2011 revealed that GTEM testing was generally preferred as being more readily implementable and yielding more consistent results that were felt to be more predictive of customers' experiences. Dipole testing was used mainly for comparative tests or to meet regulatory requirements. In consideration of the GTEM method's greater ease of implementation, its more consistent results, its preferred use in the field, and, as will be discussed, questions that remain concerning its optimum implementation, this paper addresses aspects of GTEM-based HA immunity testing only.

The IEC and ANSI GTEM-based HA test methods have several similarities:

- The applied RF field is modulated with 1 kHz, 80% AM, with the RF level measurement taken as the unmodulated carrier strength of the GTEM E-field at the hearing aid test location (hearing aid not present).
- The desired measurement result is the RF field strength that produces the same level of interference (demodulated 1 kHz signal) from the hearing aid's acoustic

output as would have resulted from a 55 dB-SPL 1 kHz acoustic input to the aid's microphone. Related requirements are established for the hearing aid's telecoil mode, referenced to an audio frequency magnetic rather than acoustic input.

- Testing is performed over frequency bands of 800 MHz to 960 MHz and about 1.5 GHz to 2.5 GHz.
- The worst-case measurement in each band determines the rating; that is, the worst-case frequency within a band at the worst-case measured orientation of the hearing aid relative to the applied field.

Differences between the two standards include the rating system applied to the measured results and the specified hearing aid rotations within the GTEM field employed to elicit an approximation to the worst-case response. It is this latter aspect, hearing aid rotational orientations, and corresponding calculation options that are the subjects of the present investigation. New 6 and 12-orientation measurements are proposed that yield improved estimations of the true worst-case orientation result.

II. Hearing Aid Rotation Considerations

A. Worst-Case Orientation

When a hearing aid wearer uses a WD such as a cell phone held at the ear, the aid is often operated next to the WD's antenna, in the antenna's near field. The positional relationship of the WD's field and its polarization relative to the hearing aid is not predictable or limited to a small range of possibilities. It makes sense, then, to search for the worst case hearing aid orientation in relation to an applied field at each test frequency. While this result may in general overestimate the interference in actual use, it does establish an upper bound and will exhibit more predictive consistency overall than would an arbitrary single orientation or limited range of orientations. Directly searching through all possible face rotations and polarizations of the hearing aid to locate the single most sensitive orientation is difficult in the case of dipole testing and more so inside a GTEM cell; it's even less practical if that orientation varies with frequency. C63.19 and 60118-13 define different approaches to approximating the desired result through evaluation of a limited number of predetermined orientations within the cell.

B. Present Search Methods

IEC 60118-13—As shown in Fig. 1, IEC 60118-13 takes a first frequency scan with the hearing aid positioned as if the user were facing the RF source, and then in each of three additional 90° rotations around the vertical GTEM E-field vector. The most sensitive of the four measurements is taken as the test result at each frequency. This method may be considered a subset of the 8-measurement immunity method defined in IEC 61000-4-20 [15], which adds a 90° rotation around the direction of propagation in each of the four positions. The 60118-13 four-measurement method yields generally good results for behind-the-ear (BTE) hearing aids. Their primary RF sensitivity tends to be to E-fields aligned with their long dimension, which is aligned with the vertically polarized GTEM E-field in this test. In the more general case, though, and particularly for in-the-ear (ITE) hearing aids, the orientation of maximum sensitivity in relation to the E- and H-fields cannot be assumed. If the maximum sensitivity of the hearing aid to E-fields happens to lie in the horizontal plane, or to H-fields in the vertical direction, these sensitivities will be missed entirely. Examples from measurements of the potential underestimation of RF susceptibility will be shown in a later section.

ANSI C63.19—The method of hearing aid rotation defined in C63.19 begins with the third position of 60118-13, as shown in Fig. 2. At a single mid-band frequency, the aid is rotated continuously through a full 360° around the vertical E-field vector, searching for a maximum response.

The hearing aid is then laid down as shown in Fig. 3 and again rotated through a full 360°. The position of the maximum of these two single-frequency rotational scans is taken as the orientation of maximum sensitivity and a full-band frequency scan is then performed at that orientation.

While this approach examines more orientations than does the 60118-13 test, E-field sensitivity aligned with the direction of propagation at the initial positioning will still be missed. The method also requires the modest complication of a small motorized table, and it does not check for frequency dependence of the selected worst-case orientation.

C. Exploring Other Possible Search Methods

In continuing the search for a minimum set of predetermined measurements from which to deduce the worst-case orientation sensitivity, it will be helpful to note that at the frequencies under consideration, the EUT may be considered electrically small, as its *ka* product (wave number times the largest dimension) is generally about 1 or less. Its directional reception may then be modeled by a system of three complex orthogonal electric dipoles and three complex orthogonal magnetic dipoles. In the reciprocal case of emissions testing, the corresponding emissions quantities may be theoretically determined in a two-port TEM cell by a multiple-rotation test sequence [16]. For extension to higher frequency emissions testing, similar results can be obtained in a single-port GTEM cell with a 6 or 9-orientation measurement sequence, if phase differences are neglected (the moments are assumed to be in phase). Such an approximation is more likely to be justified if a single dominant transmitter can be assumed [17]. If the further assumption can be made that either the E- or the H-field moments are dominant, then just three orthogonal measurements are sufficient to characterize the resultant simple dipole transmitter. Their vector sum can then be used to calculate the total radiated power from the EUT. Under the same simplifying assumptions, in the case of immunity testing, the worst-case orientation sensitivity can be found by a vector summation of three orthogonal sensitivity measurements. As will be seen, these simplifying assumptions often proved valid in actual hearing aid immunity measurements, but not always.

Three orthogonal measurement orientations can be viewed as being developed through rotation of a cube encasing the EUT that is aligned with the propagation axis and the E- and H-field vectors. The cube is rotated around one of its four long diagonals, any of which can represent an ortho-axis. When rotated in 120° increments, each axis of an X-Y-Z coordinate system aligned with the cube will align in turn with the applied E- and H-field vectors. Figure 4, reproduced from IEC 61000-4-20, illustrates a possible ortho-axis.

When combined with the conceptually infinite number of initial positioning possibilities, it is evident that the orthogonal rotation options for a given EUT are unlimited. In cases where all the above simplifying assumptions hold, though, all the positioning/rotation possibilities should yield the same three-vector sum result. In the general case, especially with larger EUTs, this consistency is not expected to hold, which has led to development of more elaborate approaches for both immunity testing and the reciprocal case of emissions testing. Reference [18] surveyed numerous approaches to waveguide emissions testing generally oriented towards open air test site correlations that involve calculations based on additional measurement orientations. One slightly more elaborate option is codified in IEC 61000-4-20, which suggests a 12-measurement, sorted three-input emissions-testing variant. This procedure selects among four initial orthogonal sum possibilities based on which of the four contains the highest individual reading. Alternatively for small EUTs, the standard recommends measuring two orthogonal sum sets (6 measurements total), and then choosing the higher of the two corresponding summations.

The general notion of a sorted three-input vector sum immunity test is further explored in this study. The goal is to establish a test method that most accurately approximates the RF sensitivity of an electrically small EUT (specifically, a hearing aid) at its most sensitive orientation relative to an applied GTEM field with the smallest set of predetermined measurement orientations. A largely empirical approach to pursuing the goal was adopted, as opposed to extensive mathematical analysis, which has the benefit of minimizing the need for a priori knowledge of the nature of the RF receivers.

III. Developing an Evaluation Data Set

A. Test Fixture

To establish a large data set for subsequent evaluation, 10 hearing aids (6 BTE and 4 ITE), were each measured in 24 possible 90°-related orientations: in each of four 90° rotations about the propagation axis with each of the six sides in turn facing the RF source. To aid in these measurements, an RF-transparent test cube was constructed of ¼” diameter Rexolite® secured with hot-melt glue, 10 cm on a side, with an internal mounting platform to center the hearing aid under test (Fig. 5). Each aid was secured in position with a small amount of adhesive putty, with a small amount also used to seal the microphone acoustic inlet ports, as needed. Silicone tubing channeled the acoustic output of the aid under test to the measurement equipment and was secured to a corner of the cube with pressure from a small nylon set screw. This cube could be positioned in the GTEM cell on an expanded foam base with good repeatability.

The 24 test cube orientations were labeled based on a right-hand coordinate system, with the initial, primary orientation having the cube’s X-axis pointing towards the RF source, its Y-axis pointing towards the right, as viewed from the RF source, and its Z-axis pointing up. The positive X, Y, and Z faces were labeled accordingly, with the top edge of each face’s rotations labeled X1, X2, X3, X4, etc, based on clockwise rotation around its respective axis.

The directly opposing sides were labeled −X1, −X2, etc. (in counter-clockwise rotation). Fig. 6 shows that the faces' axis labeling followed consistently, starting with the X face, from successive rotations around a cube diagonal (ortho-axis) extending from the upper-right-front (viewed from the RF source) to the lower-left-rear (through the 1st and opposing octants of the defined 3-dimensional coordinate system). (This orientation labeling is further illustrated in the Appendix.) The experimental data obtained consisted of interference measurements at each of the 24 orientations for each of the 10 aids, at a single frequency for each aid (240 measurements total).

The orientations illustrated in Fig. 6, +X1, +Y1, and +Z1, represent one possible set of orthogonal measurements. Due to the square law detection characteristics of the offending hearing aid semiconductor junctions, the three measured levels of recovered audio at these three orientations can simply be added to obtain the result that, in the case of a single ideal dipole receiver, would have been obtained from a single recovered audio measurement taken in the maximum sensitivity orientation.

B. Test Methodology

Testing was carried out at the facilities of the Center for Devices and Radiological Health (CDRH) of the Food and Drug Administration, Silver Spring, MD. Each HA was positioned in an EMCO model 5317 GTEM (maximum septum height of 175 cm) at septum heights of 60 cm and nearer the throat at a septum height of 34.6 cm. The test cube was positioned midway between the septum and the GTEM floor and aligned so as to make equal angles with each of the 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. Each of the 10 hearing aids was tested at a single selected frequency between 836 MHz and 1.79 GHz and at an RF power level chosen so as to ensure that the detected audio interference stayed in a useful portion of the aid's dynamic range. The excitation level for each aid was held constant for all of its 24 measurements.

Five meters of 4mm inside diameter tubing coupled the hearing aid's acoustic output through the floor of the GTEM to a custom-built, switchable gain microphone/amplifier combination (Fig. 7), whose output fed a fixed-gain 16-bit analog-to-USB converter, in turn feeding a laptop computer. The hearing aids were operated in their linear mode (no level compression or active processing) and were confirmed to be excited in their accurate square law detection range with respect to RF interference (below output clipping). The response of the hearing aids in conjunction with the tubing and the following test interface equipment didn't need to be characterized as long as the test setup remained unchanged throughout the testing, because the experiment did not require referring the measured interference back to an equivalent hearing aid acoustic input.

The RF test signal used did not employ 80%, 1 kHz AM, as specified in the ANSI C63.19 and IEC 60118-13 standards. For reasons relating to the larger study of which this investigation was a part, simulated GSM cell phone modulation pulses were employed. These consisted of 576 μsec pulses repeating every 4.615 msec, yielding a fundamental frequency of 216.7 Hz. Extremely narrowband filtering in the processing software (Adobe Audition) selected just the 4th harmonic of the detected pulse stream at 867 Hz while rejecting noise outside a ±4 Hz bandwidth around that frequency. This filtering greatly increased the measurement sensitivity in the presence of extraneous audio frequency noise in comparison to a broadband measurement. The 4th harmonic was selected for measurement instead of the fundamental, as its amplitude is almost as strong as the fundamental, while sitting in the mid-audio frequency range where the hearing aids could be assumed to have strong gain. The E-field strengths of the simulated GSM pulses at the hearing aid location ranged from 38 to 212 V/m.

IV. Sensitivity to Initial EUT Orientation

The various described search methods can yield varying results, depending on the initial EUT orientation. Working with various subsets of the 24 measurements taken on each of the 10 tested aids enabled examination of this variability.

A. Orthogonal Sums

Starting in each of the 24 measured cube orientations and rotating around each of the four possible ortho-axes (long cube diagonals), 96 possible orthogonal rotations result, which reduce to 32 when order is ignored (8 unique orientation combinations for each of the four ortho-axis rotations). If all the previously discussed simplifications held (i.e., the receiver behaved as a single ideal magnetic or electric dipole), vector sums based on these 32 unique combinations would all yield the same result. This did not turn out to be the case. It does seem reasonable, however, to propose that the maximum of these sums represents a very good stand-in for the desired result of the worst-case orientation sensitivity, if that orientation could have been found by some trial-and-error means and the sensitivity then measured directly.

While it might be expected that the maximum of the 32 orthogonal sums could exhibit a tendency to slightly overestimate the desired quantity in practice, due to its upward capture of the inevitable measurement uncertainties, the experimental data shows that a substantial majority of the possible orthogonal sums for all the hearing aids tested approach a consistent maximum limit for each aid, with no sums significantly exceeding that limit. This would seem to further support the proposition that the maximum of the orthogonal sums is a reasonable stand-in for the desired quantity.

The histogram of Fig. 8 shows the degree of inconsistency obtained when calculating the 320 unique orthogonal sums derived from the experimental data (32 for each of the 10 hearing aids). Each result has been normalized to the maximum result for its aid's 32 sums. The plotted decibel results can be considered as normalized RF sensitivities, with the 0 dB reference being the maximum sum result for each aid. (Due to the hearing aid square law detection mechanism, these same differences would be represented by twice these decibel amounts if the plotted quantities were the measured acoustic outputs of the hearing aids.) While the majority of the sums are within about 1 dB of the maximum (bin boundaries are at −0.5 dB, −1.5 dB, etc.), revealing a clear tendency towards a bounded upper limit, there are many of the sums that do not approximate that maximum well. The simplifying assumption of a single, ideal dipole receiver does not uniformly hold. Clearly, if an immunity test were limited to a single arbitrarily chosen orthogonal sum, the result could be expected to depend unpredictably on the particular rotation chosen and the initial orientation of the EUT.

B. IEC 60118-13

By way of comparison, taking the maximum of the four horizontal plane rotations defined by 60118-13 yields the results shown in Fig. 9, again normalized to the maximum orthogonal sum. Some of the tested hearing aids, especially the BTE aids, are fairly well represented by this simple measurement, due to the coincidental alignment of the applied E-field with their dominant E-field receiving antennas.

However, if all of the six unique cube orientation sequences are included that result from all of the differing initial orientation possibilities, the results of Fig. 10 are obtained. The contrast clearly reveals the orientation sensitivity of the test method. Seven of the 36 BTE aid results, from three of the BTE aids that were well represented in Fig. 9, are not plotted, as rotating to a laid-down instead of upright orientation leaves all four of the contributing measurements for each in the noise floor.

C. ANSI C63.19

Continuous fine-grained rotation measurements according to the C63.19-2011 GTEM method, as illustrated in Fig. 2 and 3, were not taken. An approximation to the upright and laid-down rotation sequences using the measured 90° cardinal points can be readily constructed by taking the maxima of the appropriate 12 unique pairs of the 6 rotation sequences of Fig. 10. The results, plotted in Fig. 11, show some reduction in the lowest readings, achieved in exchange for the greater measurement density. The particular difficulty in the previous orientation sequences with EUTs having sensitivity strongly aligned with a cube axis is only partially relieved, though, as revealed by the remaining low results and the 5 (of 72) BTE results having all 8 contributing measurements in the noise floor (not plotted).

D. IEC 61000-4-20

A closely related sequence is the 8-measurement immunity test of IEC 61000-4-20. The four horizontal rotations of 60118-13 (shown in Fig. 1, data in Fig. 9) are combined with 90° rotations in each position around the propagation axis, and the highest of the 8 readings taken. This procedure exposes the four initially horizontal cube faces to the RF field in both polarizations, but doesn't address the initial top and bottom faces. Fig. 12 shows more consistency than the previous examples, which can be attributed to the fact that the procedure aligns all of the cube's axes with both the E and the H-field in at least one of the 8 measurements. The remaining underestimation of the actual worst-case orientation RF sensitivity can be attributed to the lack of any vector summation and that two of the six cube faces always remain unexposed.

V. Towards a Minimal Measurement Subset

A. Rotational Dependence

It is readily evident that the 24 measurements contributing to the 32 orthogonal sums contain redundancy, in that each of the two polarizations of each of the six faces is represented twice among the listing: e.g., +X1 and +X3, +Y2 and +Y4, −Z1 and −Z3, etc. Each of these pairings represents a 180° rotation about the propagation axis. As the EUT's under consideration are small in comparison to any GTEM field gradients, the pairings should yield identical, interchangeable results. One result of such an equivalency is that half of the 32 orthogonal rotations can be considered equivalent to the other half; i.e., the rotation +X3, +Y3, +Z3 is equivalent to the rotation +X1, +Y1, +Z1. Another result is that the list of sums equivalent to the 32 can be expanded, although these new sums do not correspond to true coordinate system rotation of axes (obtained through rotation about an ortho-axis). An additional 96 such quasi-orthogonal sums can be generated through interchanges of equivalent rotations about individual axes of the 32 orthogonal sum components. (This sum combination development is further discussed in the Appendix.)

While the inevitable measurement uncertainties did result in minor differences in the test data between the theoretically identical paired measurements, the differences were small and resulted in generally small differences in the corresponding sums. 98% of the 960 calculated quasi-orthogonal sums differed by no more than 1 dB from their corresponding orthogonal sums. Those showing the larger changes were associated with those sums, visible in Fig. 8, that were much smaller than their aid's maximum sum, having all three contributing terms much smaller than the highest measurements, and therefore having greater sensitivity to error sources such as minor EUT positioning inconsistencies. Quasi-orthogonal sums nearer their aid's maximum sum showed very little change. In fact, the maxima of these additional sums differed by no more than 0.1 dB from the maxima of their corresponding 32 orthogonal sums, reinforcing both their practical equivalency and the notion that the maximum of an aid's orthogonal sums represents a consistent reference. Polarization-invariant interchanges (substituting +X3 for +X1, etc.) can be considered benign and do not materially affect the important resultant sums.

This interchangeability is not expected to carry over to 180° rotations about other axes, such as the vertical axis, as an opposite face of the hearing aid is then addressed and the polarity relationship between the E- and H-fields with respect to the EUT is reversed. Such a vertical axis rotation is represented by, for example, an exchange of the −X1 orientation for the +X1. That this can yield very different measurement results is illustrated in Fig. 13. The data shown are calculated from the measured quantities (square law-detected recovered audio levels) that contribute to the orthogonal sum calculations. These quantities are taken after the hearing aid square law detection and normalized to each aid's maximum orthogonal sum value of 1. The histogram shows the differences in these quantities resulting from the differing 180° rotations. They are shown for both the benign rotation around the propagation axis (for the three positive-numbered faces) and the contrasting rotation around the vertical E-field vector. (21 of the 120 differences for the first rotation were near residual noise levels and are not included; 22 of 120 for the second case are not included.) Some of the changes resulting from the latter rotation can approach the entire normalized maximum sum value of 1, obviously contributing to a very different orthogonal sum. Within individual opposing paired measurements (e.g., −X1 vs. +X1), differences of 10 and even 15 dB in RF sensitivity were seen.

B. Maximal Sums

The 128 total (32 + 96) orthogonal and quasi-orthogonal sums may be divided into two groups: odd and even. The odd group consists only of sums involving ±X1, ±X3, ±Y1, ±Y3, ±Z1, and ±Z3, and correspondingly for the even group. Together, the 128 sums include all possible 3-face sums that consist of measurements that successively align both the E- and H-fields with the three orthogonal axes of the test cube. (Intermixing of even and odd orientations in the same sum does not accomplish this.) Each odd or even group aligns the measured faces in one of their two distinct polarizations. Given the interchangeability of +X1 and +X3, etc. and the non-interchangeability of +X1 and −X1, etc., the maximum sum of the 64-member odd group of sums can be given, among 64 equivalent possibilities, by (relating square-law detected quantities):

$$MAX_{odd}=MAX(+X1,-X1)+MAX(+Y1,-Y1)+MAX(+Z1,-Z1) \quad (1a)$$

Relating linearly detected field strength sensitivities rather than square-law detected quantities, the equivalent formula appears more as conventional vector addition:

$$MAX_{odd}=\sqrt{(MAX(+X1,-X1))^2+(MAX(+Y1,-Y1))^2+(MAX(+Z1,-Z1))^2} \quad (1b)$$

Similarly, the maximum sum of the 64 member even group of sums can be given, also among 64 equivalent possibilities, by:

$$MAX_{even}=MAX(+X2,-X2)+MAX(+Y2,-Y2)+MAX(+Z2,-Z2) \quad (2a)$$

$$MAX_{even}=\sqrt{(MAX(+X2,-X2))^2+(MAX(+Y2,-Y2))^2+(MAX(+Z2,-Z2))^2} \quad (2b)$$

(Equation 2a relates square-law detected quantities and 2b relates linearly detected field strengths.)

The quantities defined by these equations in their respective contexts, along with all the equivalent quantities generated by equivalent substitutions (+X3 for +X1, for example), will be referred to subsequently as maximal sums. The maximum of all 128 unique maximal sums (odd and even) is exactly equal to the maximum of the 128 orthogonal and quasi-orthogonal sums and, by the interchangeability of +X1 and +X3, etc., is then equivalent to the established reference of the maximum of the original 32 orthogonal sums.

Taking the maximum of a single pair of odd and even maximal sums constructed from just 12 measurements yields less perfect consistency, but still results in a close equivalency to the reference. Any group of 12 measurements that addresses all six faces of the cube in both polarizations can be used to calculate a pair of odd and even maximal sums, including the straightforward set illustrated in (1a,b) and (2a,b). There are $(64)^2$ (4096) such possible odd-even maximal sum pairings. Fig. 14 tallies the differences of these pairings from the reference of the maximum of the 32 orthogonal sums for the 10 tested aids (40,960 total). (This plot and subsequent maximal sum plots are not separated into BTE and ITE results, as there is no orientation bias in the method that might be expected to result in significant differences between the groups, and none is observed.) The calculated RF sensitivity data exhibits an average value of −0.2 dB and a range of −1.1 to 0.1 dB. It is clear that a single 12-measurement based paired maximal sum can still be considered practically equivalent to the maximum of the 32 orthogonal sums and thus, by the original proposition, yields a close approximation to the goal of the single-measurement RF sensitivity result that would have been obtained at the most sensitive orientation.

But 12 measurements are only a modest improvement in measurement simplicity over the original 24. How necessary is it to determine both an odd and an even maximal sum? Fig. 15 shows the results from examining separately each of the 128 6-measurement odd and even maximal sums in comparison to the paired 12-measurement-based results of Fig. 14. The calculated RF sensitivity equivalency data now exhibits an average value of −0.5 dB and a range of −1.5 dB to 0.1 dB. While showing modestly greater differences from the orthogonal sum maximum than in the 12-measurement paired maximal sum case, the results are still generally very close and still not far from the degree of measurement uncertainty that could ordinarily be expected to result from minor positioning errors and short-term equipment drift.

It should be expected that when the actual maximum orthogonal sum (of the original 32) comes from the odd group, then the odd maximal sums should give a better equivalency than the even maximal sums, and vice versa. This is seen to be generally the case in Fig. 16, which presents the same data as the 6-measurement data of Fig. 15, but with the *matched* and *unmatched* conditions separated. The difference between the two groupings, though, is fairly small (−0.25 dB matched average vs. −0.77 dB un-matched average, with similar overall ranges). Judged empirically, at least for the small EUTs under consideration, little potential accuracy is lost in measuring and calculating just one maximal sum, either the “odd” or the “even”, needing just 6 measurements rather than 12.

A practical small EUT immunity test may consist of the 6 measurements associated with any one of the 128 maximal sums that are equivalent to the example maximal sums of (1) or (2). An appropriate set of measurements may be most readily arrived at with an initial three measurements at orientations established through rotation about an ortho-axis (+X1, +Y1, +Z1, for example) followed by their opposite orientations determined after 180° rotation of the EUT and the ortho-axis about the E- or H-field axis (−X1, −Y1, −Z1, for example). A 12-measurement paired maximal sum test would find the maximum of an odd and an even maximal sum. After the first 6-measurement maximal sum measurements are taken, a second 6-measurement maximal sum’s starting orientation is then established by a 90° rotation in either direction about the propagation axis from any of the first’s sum’s measurements orientations.

VI. Comparison to Other Related Approaches

A. IEC 61000-4-20 Small EUT emissions test

The proposed 6-orientation maximal sum immunity test bears some similarity to the 6-orientation small EUT emissions test of IEC 61000-4-20 briefly mentioned above. In that test, emissions in 6 of 12 specified 90°-related orientations are taken, corresponding to a choice of two odd or two even orthogonal rotations, although not sensing all 6 rotation faces. From a selected initial orientation, three orthogonal rotations are taken around a specified one of the four ortho-axes and the emissions vector sum calculated. Returning to the initial orientation, the EUT is rotated 180° around the vertical E-field vector and the procedure repeated, but using the same ortho-axis (which is not rotated). The higher of two such similarly rotated emissions vector sums is selected as the measurement result. In contrast, the proposed 6-measurement maximal sum immunity method effectively finds the maximum of half (16) of the 32 possible orthogonal sums, or half (64) of the total 128 possible orthogonal and quasi-orthogonal sums. Again comparing to the orthogonal sum maximum, Fig. 17 plots the calculated results for the 10 hearing aids based on applying the IEC 61000-4-20 highest-of-two sum method (here applied to immunity measurements rather than emissions), for each of the 12 unique orientation pair possibilities calculable from the acquired data set. While the procedure represents a decided improvement over a single arbitrary orthogonal sum (compare to Fig. 8), it does not result in the consistency of the 6-measurement maximal sum method, re-tabulated for comparison here in red.

B. Highest of Two Opposing Sums

As noted previously, the 61000-4-20 small EUT emissions test does not rotate the cube such that all 6 faces address the GTEM apex, in that the initial top surface never faces the apex. If, in going from the first orthogonal set to the second, the rotation ortho-axis is rotated with the EUT around the vertical E-field vector (equivalent to leaving the EUT in place and rotating the GTEM cell), then the resultant orientations provide for all 6 faces to be addressed and are, in fact, the same as could be used in finding the maximal sum. For this possible modified test, though, two separate sums are calculated and the higher taken, in contrast to the maximal sum calculation. Fig. 18 compares the results of this calculation for the 10 tested aids, based on the 16 unique odd and 16 unique even orthogonal sum pairing possibilities that address all six cube faces (the pairings obtained by 180° rotation of both the EUT with its selected ortho-axis about the E or the H-field vector). These results are compared to the 64 odd and 64 even maximal sums generated from the same measurements. There is a decided improvement over the non-opposing sums of Fig. 17, but the "highest of two sums" selection still does not make as effective use of six contributing measurements as does the maximal sum calculation.

C. Highest of Opposing Odd and Opposing Even Sums

If the maximum of opposing odd and opposing even sums is taken (12 measurements total, addressing both polarizations of all six faces), the improved results shown in Fig. 19 are now on a par with the 6-measurement maximal sum results, but still fall short of the 12-measurement paired maximal sum results of Fig. 14. The implication of these last two comparisons is that by employing the maximal sum calculation instead of simply taking the highest of the calculated orthogonal sums, the tester can either reduce the test time by half for the same likely underestimation error (taking 6 vs. 12 measurements), or, for the same number of measurements, significantly reduce the likely underestimation error.

D. Summarizing the Comparisons

It is clear that, for a given number of such measurements, maximal sums approximate the established target of the maximum of the 32 orthogonal sums more closely and more consistently than do any of the other approaches examined. This can be seen clearly in the summarizing graph of Fig. 20, which charts the ranges and averages of the calculated RF sensitivity results, normalized to the target, for each of the discussed measurement approaches for the 10 tested hearing aids over the range of possible EUT initial orientations. While most of the approaches yield fairly good results on average, some can be expected to significantly underestimate the established goal a portion of the time. Any of the approaches that make use of opposing orthogonal sums (the right-hand four in the figure) and thus address all six faces of the test cube yield good results and run little risk of major sensitivity underestimation. The maximal sum approach, however, yields more consistent, orientation-independent results than do approaches that, although using the same measurements, simply choose the highest of the measured orthogonal sums. The 12-measurement maximal sum results should be equivalent to the stated 0 dB reference (given the interchangeability of 180° rotations about the propagation axis), so the indicated deviations for this case are due solely to measurement uncertainty. In practice, the 6-measurement maximal sum approach yields results that are only slightly less consistent. A test methodology based on it can be well-recommended for the practical measurement of hearing aid RF immunity.

VII. Applying the 6-measurement Maximal Sum Method

Implementation of the 6-measurement maximal sum method is straightforward. The testing will typically take place in a GTEM cell, but could also be performed in a larger free-field environment. The EUT can be mounted in the center of an RF-transparent cube, as was done for this experimentation, and the cube placed in an initial orientation aligned with the E- and H-field vectors and the propagation axis. The cube is rotated about an ortho-axis, which can be any of its long diagonals, in 120° steps, through each of three orthogonal orientations. Alternative mounting fixtures can be readily envisioned that result in the same rotational orientations. A pictorial diagram of an appropriately angled rotation fixture is depicted in Figs. A.2b and A.2c of IEC 61000-4-20.

Following the first set of three orthogonal measurements, the cube or other equivalent fixture, along with its established ortho-axis of rotation, are rotated together 180° in the horizontal plane about the E-field vector (which will generally be more convenient than about the H-field vector), and another set of three orthogonal measurements taken. Fig. 21 repeats the initial rotation set depicted in Fig. 6, followed by the matching set obtained with this procedure. Each measurement is paired with its directly opposing measurement, and the highest readings from each of the three pairs combined to form the maximal sum, as illustrated in the example formulas (1a), (1b), (2a), and (2b). For measurements over a band of frequencies, a scan is performed at each of the six orientations, with the maximal sum found independently at each of the incremented frequencies.

When the EUT is a hearing aid, the measured quantity is its acoustic output, which is transferred to the measurement microphone and associated apparatus through silicone tubing. The excitation signal typically consists of an RF carrier, amplitude-modulated at 80% peak by a 1 kHz sine wave. Semiconductor junctions within the hearing aid act as square-law detectors, which result in a recovered 1 kHz audio signal, along with a five times lower level of 2 kHz signal. The level of both of these recovered audio frequency components vary as the square of the received RF field strength. The vector sum equivalent can thus be found by simple addition of the three selected readings, as illustrated in (1a) and (2a). By the argument of this paper, supported by the presented data, this result closely represents the level that would have been measured directly, had the hearing aid been positioned in its most sensitive orientation to the applied field. Through prior or post characterization of the net electro acoustic gain from the hearing aid acoustic input and on through the output tubing to the measurement apparatus, the calculated measurement quantity is referred back to the hearing aid input as an equivalent input sound pressure level.

It is important that the hearing aid be placed in a stable, linear mode of operation, to ensure that there are no dynamic gain changes or other processing effects. Equally important, the RF excitation level and hearing aid gain setting (if available) both need to be controlled to avoid possible overload of the aid or other related high-level deviation from square law behavior. When the necessary excitation levels vary from established test standards, results can be extrapolated to correspond to standard levels by remembering that, due to the square-law detection, a 1 dB change in RF excitation results in a 2 dB change in recovered audio level.

VIII. Conclusion

It is generally regarded that the desired RF immunity measurement result for a hearing aid is the immunity that would be measured in the aid's most sensitive orientation in relation to an applied RF field. Recommended methods presently include placing the aid in a GTEM cell using one of two related but differing rotation sequences. This paper has presented a new maximal sum method, as a variation on and an extension to present sorted three-input vector sum emissions and immunity testing methods. Setting as a reference goal the maximum of all 32 possible orthogonal sums generated from a complete set of 24 possible 90°-related orientations, it was shown that, for the ten aids tested, the 6-measurement maximal sum method yielded calculated sensitivity results differing from the reference by an average value of −0.5 dB, and covering a range of −1.5 dB to +0.1 dB. These results were superior to those obtained from other examined approaches of comparable complexity, with all results calculated from the same experimental data set. In comparison, the other approaches showed increased tendencies towards sensitivity underestimation.

While the justification presented for the maximal sum method has been largely empirical, it is also based partially on the characterization of the EUT as being electrically small. While data was not collected for EUTs not meeting this criterion, it is reasonable to project that the accuracy of the method should not degrade precipitously at frequencies somewhat higher than the tested range of 836 MHz to 1.79 GHz or with EUTs that are somewhat larger than the tested hearing aids. It might also be expected that the accurately testable frequency and size ranges could be further extended with a 12-measurement paired maximal sum, formed by taking the maximum of paired odd and even maximal sums. These projections could be areas of further investigation. The maximal sum method might also be adapted to emissions testing of small EUTs, in cases where the maximum emission irrespective of direction is of interest.

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 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, Perry Wilson for helping to clarify some theoretical concepts, Eric Krenz and Paul Moller for careful reading and comments on the manuscript, and the reviewers for their helpful input.

Biographies

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 authored or co-authored papers published in the Journal of the Audio Engineering Society and the Journal of the American Academy of Audiology, and holds 18 patents. He is presently participating in a research project exploring the correlation between cell phone near-field emissions measurements, hearing aid RF immunity measurements, and the measured in-use combined interference. Mr. Julstrom is also a member of the Audio Engineering Society and an associate member of the Society of Automotive Engineers. In 2011, he received the President's Award from the Hearing Loss Association of America.

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 1996, she began her clinical fellowship in audiology at the University of Maryland Medical System in the Otolaryngology Department and received her certificate of clinical competence in 1998. Since 1998, she has worked in the Technology Access Program at Gallaudet University as a research audiologist. Currently, she is an investigator on two Rehabilitation Engineering Research Center grants, one on telecommunications access and another on hearing enhancement. Her research interests include issues related to telephone compatibility with hearing devices and voice telecommunications accessibility for individuals with hearing loss. She has contributed to both ANSI and TIA standards and has authored or coauthored papers published in a variety of speech and hearing journals. She and Mr. Julstrom are co-investigators on a project exploring the correlation between cell phone near-field emissions measurements, hearing aid RF immunity measurements, and the measured in-use combined interference. Ms. Kozma-Spytek is a member of the American Speech Language Hearing Association. In 2005, she received an award from the Hearing Loss Association of America for her work in telecommunications accessibility for hard of hearing people.

Brian B. Beard received the B.S. degree from the U.S. Air Force Academy, USAFA, CO, in 1973, in electrical engineering and the M.S. and the Ph.D. degrees from Vanderbilt University, Nashville, TN, in 1993 and 1995, respectively, both in biomedical engineering. His Ph.D. thesis work was based on instrumentation for in vivo measurement of cardiac dynamics. His current research interests include RF dosimetry and auditory prosthetics. He has contributed to both IEEE and ASTM standards and has authored or co-authored papers on medical instrumentation and specific absorption rate (SAR). Currently, he is with the U.S. Food and Drug Administration's Center for Devices and Radiological Health, Silver Spring, MD.

References

1. FCC Publication RM-8658, WT Docket No. 01-309. Washington, DC: Aug. 2003 Report and Order in the Matter of Section 68.4(a) of the Commission's Rules Governing Hearing Aid-Compatible Telephones.
2. Global System for Mobile Communication (GSM). http://www.gsm.org/
3. ANSI Standard C63.19. 2011. Methods of Measurement of Compatibility between Wireless Communications Devices and Hearing Aids.
4. IEC Standard 60118-13. 2011. Electro acoustics - Hearing aids - Part 13: Electromagnetic compatibility (EMC).
5. Levitt H, Harkins J. Special issue, "Wireless Telephones and Hearing Aids: New Challenges for Audiology". J Am Acad Audiol. Jun.2001 12
6. Preves D. Hearing aids and digital wireless telephones. Semin Hear. Jan.2003 24:43–62.
7. Kozma-Spytek L, Harkins J. An evaluation of digital cellular handsets by hearing aid users. J Rehab Res & Dev. Jul-Aug;2005 42:145–156.
8. Srinivasan, S., Schlegel, RE., Grant, H. Evaluation of the Interaction between Wireless Phones and Hearing Aids, Phase II-B: Clinical Determination of the Speech-to-Interference Ratio. Center for the Study of Wireless EMC, Univ. of Ok; Norman, OK: 1998. EMC Report 1997-2
9. Killion, M. Digital cellphone progress report. presented at the Hearing Industry Association Annual Meeting; Palm Springs, CA. Feb. 2000;
10. Levitt H, Kozma-Spytek L, Harkins J. In-the-ear measurements of interference in hearing aids from digital wireless telephones. Semin Hear. Feb.2005 26:87–98.
11. 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. Sep.2011 22:528–541. [PubMed: 22031677]
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 Star-key measurement comparisons. presented at the ANSI C63.19 WG3 meeting; Piscataway, NJ. April 2009;
14. Julstrom, S. Comparison of Emissions and Immunity Data. Jan. 2010 submitted to ANSI C63.19 WG3
15. IEC Standard 61000-4-20. 2010. Electromagnetic compatibility (EMC) – Part 4–20: Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides.
16. Sreenivasiah I, Chang DC, Ma MT. Emission Characteristics of Electrically Small Radiating Sources from Tests Inside a TEM Cell. IEEE Trans Electromagn Compat. Aug; 1981 EMC-23(3): 113–121.
17. Wilson P. On Correlating TEM Cell and OATS Emission Measurements. IEEE Trans Electromagn Compat. Feb; 1995 31(1):1–15.
18. Harrington, TE. Catalog of TEM waveguide radiated emissions correlation methods. IEEE Int Symp Electromagn Compat; Minneapolis, MN. Aug. 2002 p. 486-491.

Appendix

EUT orientations and sum combination development

The paper cube of Fig. 22 can be constructed as an aid in visualizing the EUT rotations. The labeling of the 24 face orientations is as described in section III-A.

Section IV-A states that the total of 32 unique orthogonal combinations comes from rotations about each of the four ortho-axes (8 each). For rotations about the ortho-axis passing through the upper right corner as viewed from the RF source (as shown in Fig. 6), the 8 combinations are:

+X1	+Y1	+Z1
+X2	−Y4	+Z4
+X3	−Y1	−Z3
+X4	+Y2	−Z4
−X1	−Y3	+Z3
−X2	−Y2	−Z2
−X3	+Y3	−Z1
−X4	+Y4	+Z2

The eight combinations resulting from rotations about the ortho-axis passing through the lower left corner are related to these eight through the benign polarization-invariant interchanges of each component discussed in section V-A. For example, this second group includes the entry +X3, +Y3, +Z3. A similar relationship exists between the remaining two rotation axis groups.

Applying the benign substitutions to just the second and third components of the first entry in the above listing (instead of to all three components) yields three additional equivalent combinations:

+X1	+Y3	+Z1
+X1	+Y3	+Z3
+X1	+Y1	+Z3

These entries were termed “quasi-orthogonal” combinations, as they do not follow a true rotation of axes. The measurement results are, however, equivalent to the parent combination. Expanding each of the 32 orthogonal entries similarly yields the total 128 orthogonal and quasi-orthogonal sums.

The listing of 128 valid sums can be developed alternatively by ignoring the mathematical distinction of quasi-orthogonal sums vs. the true orthogonal sums derived from rotation of the X,Y,Z coordinate system axes, and instead, simply accepting all orientation combinations that align all three axes of the EUT with both the E-field and the H-field vectors. Of the 8^3 (512) possible X, Y, Z orientation combinations, only those that are all odd or all even by the orientation labeling adopted satisfy this criterion. There are 4^3 (64) odd and similarly 64 even combinations meeting the criterion.

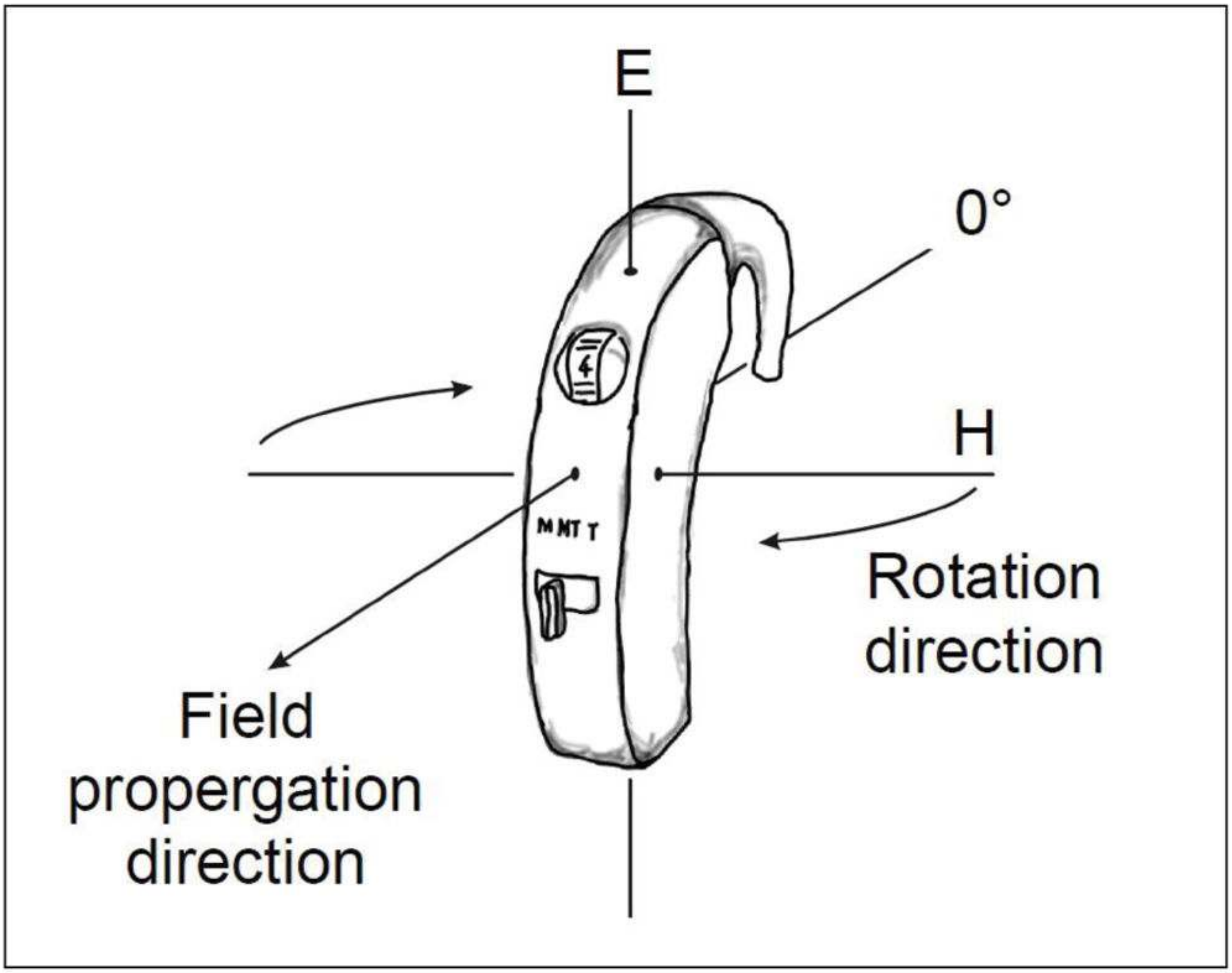

Fig. 1.
Pictorial from IEC 60118–13 showing the initial orientation of a BTE hearing aid under test and the rotation direction for the three 90° rotations.

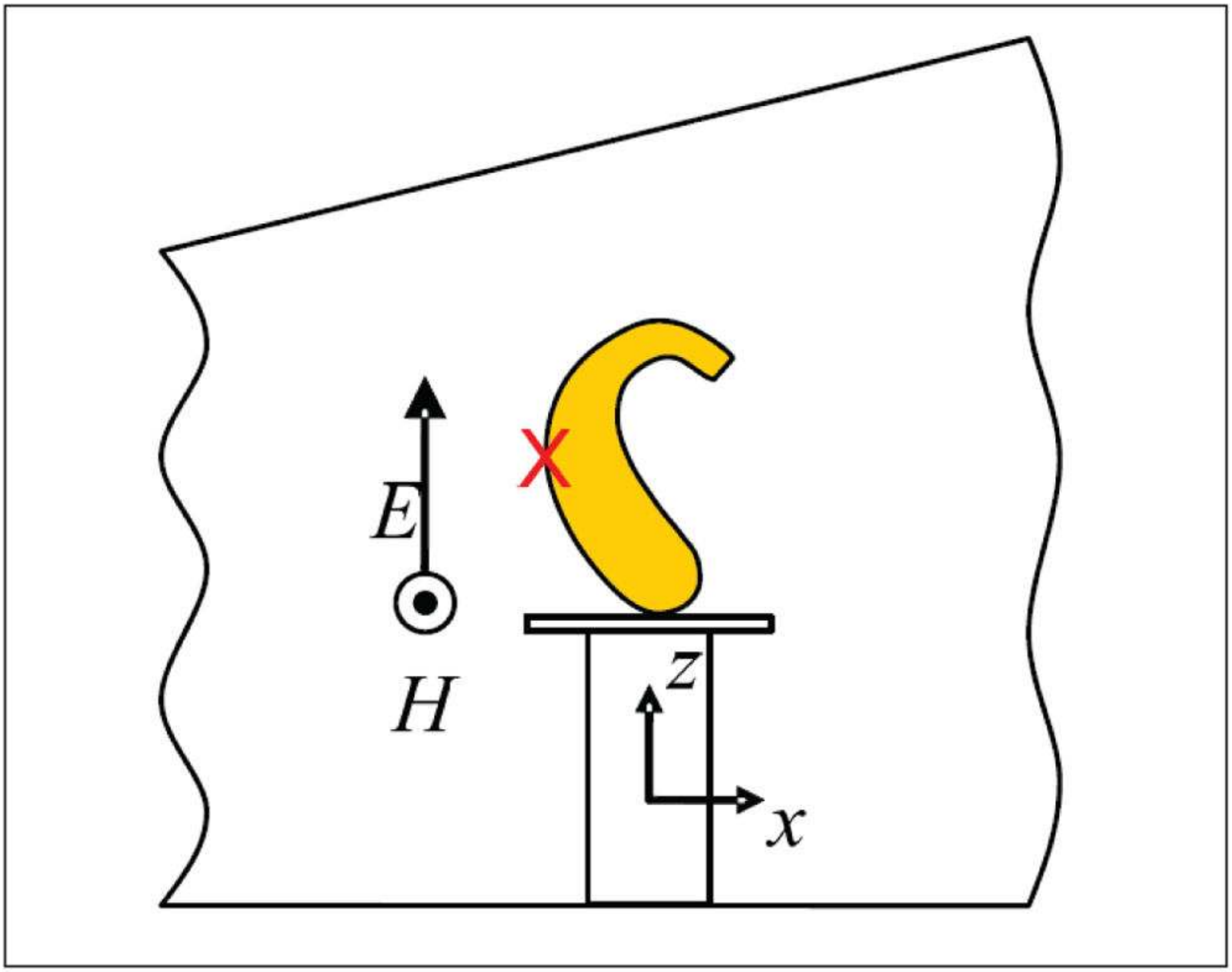

Fig. 2.
Pictorial from ANSI C63.19-2011 showing the initial orientation in a GTEM cell of a BTE hearing aid under test.

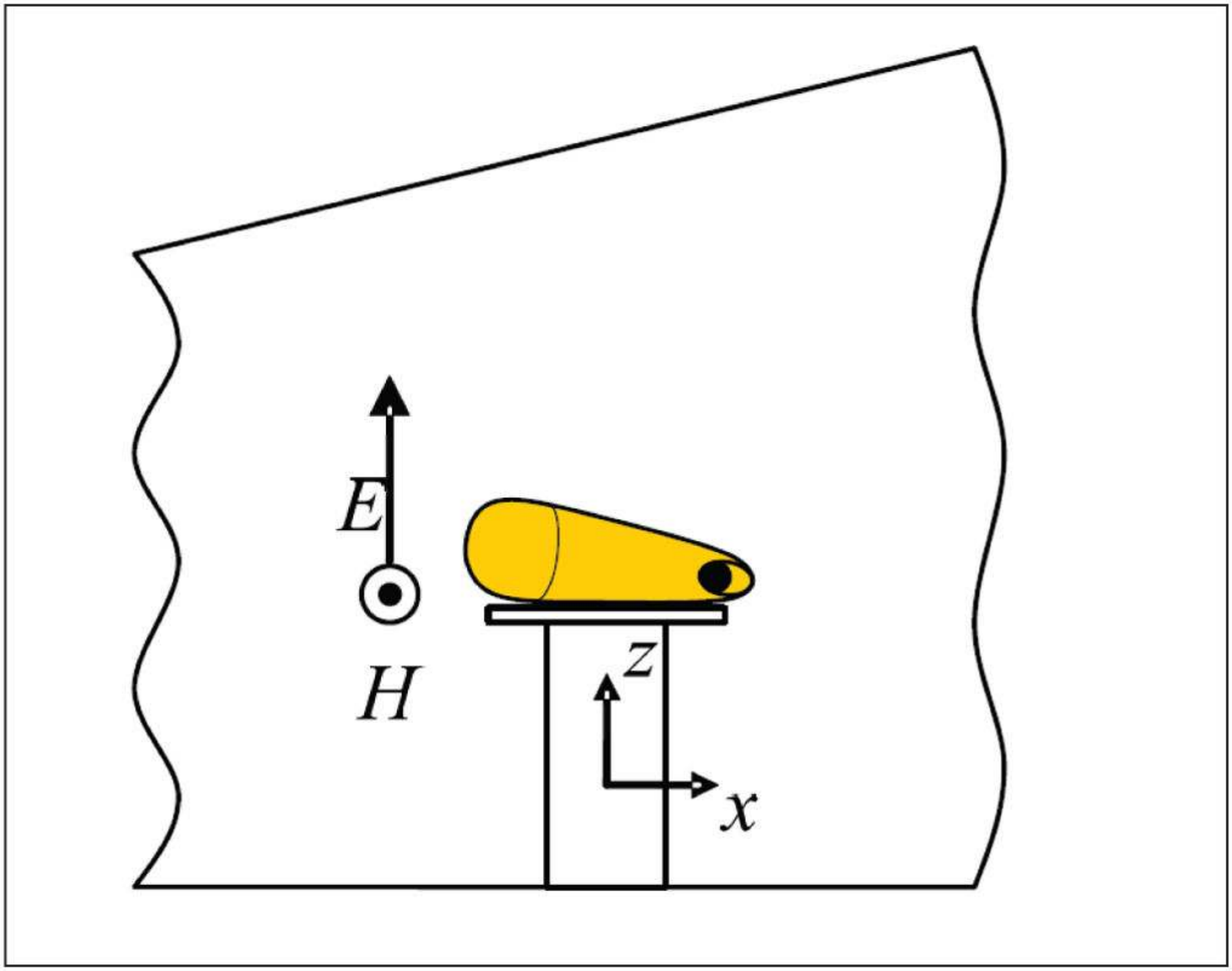

Fig. 3.
Also from ANSI C63.19-2011, pictorial showing a second hearing aid positioning, before rotation.

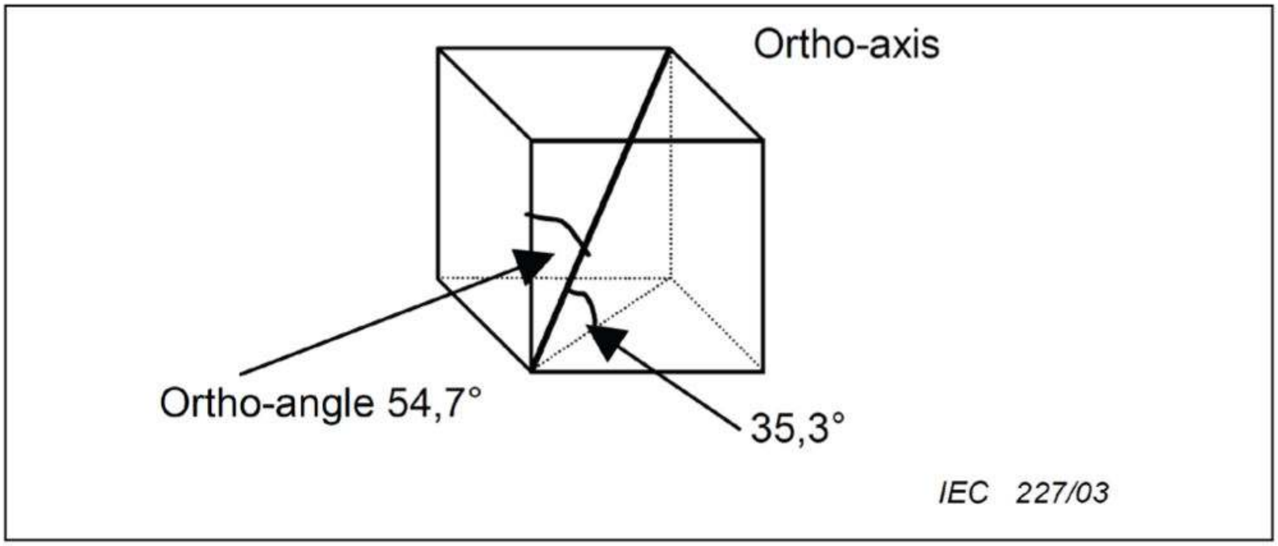

Fig. 4.
From IEC 61000-4-20, pictorial illustrating one of four possible ortho-axes of a cube aligned with the E and H field vectors and the field propagation axis.

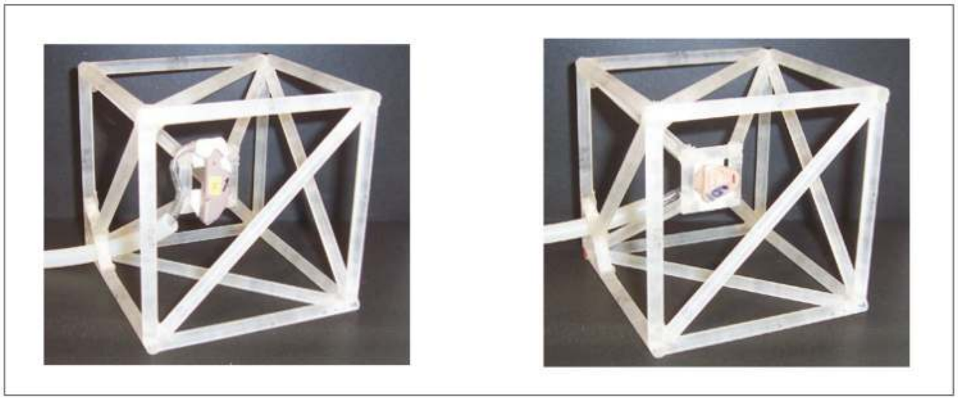

Fig. 5.
Test cube constructed of ¼” dia. Rexolite®, with mounted BTE (left) and ITE (right) hearing aids and acoustic output tubing.

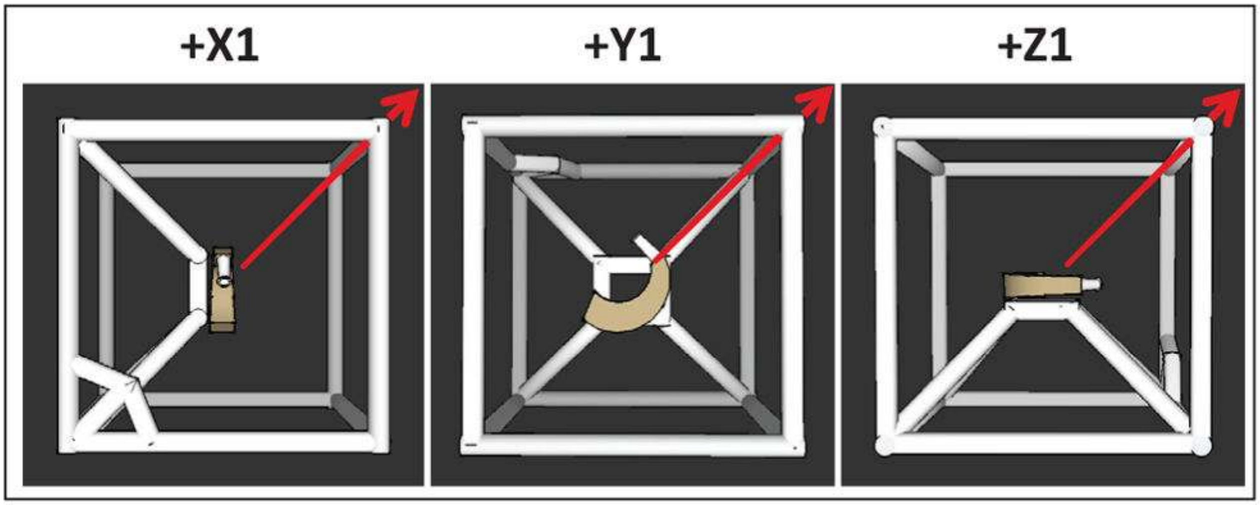

Fig. 6.
Three orthogonal orientations created by successive 120° rotations around a cube diagonal (ortho-axis) extending from the upper-right-front to the lower-left-rear, as viewed from the RF source.

Fig. 7.
Switchable gain microphone/amplifier combination. Multiple outputs can feed an A/D converter, an oscilloscope, and computer loudspeakers for audible monitoring.

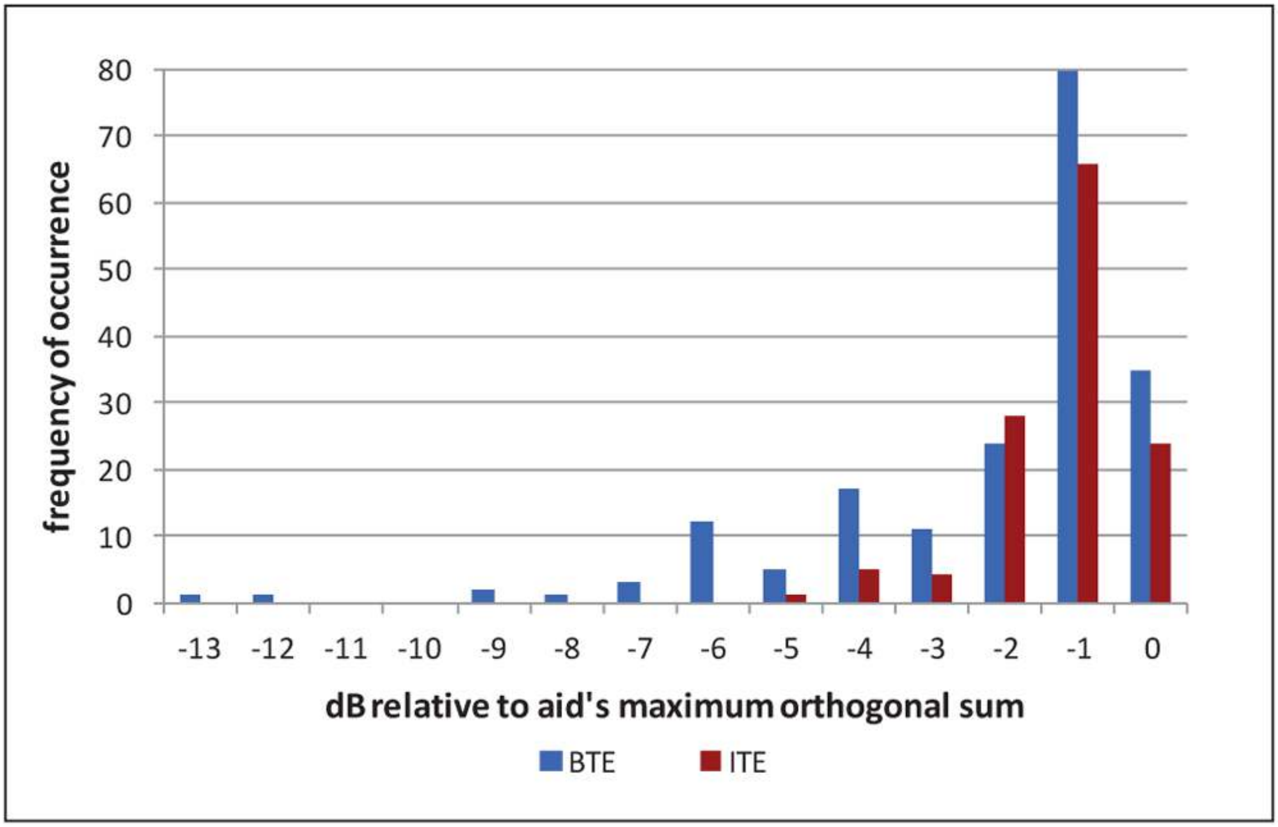

Fig. 8.
RF sensitivities calculated for the 10 tested aids from all 32 unique orthogonal sums, normalized to the maximum sum for each aid, with results for the 6 BTE aids and 4 ITE aids plotted separately.

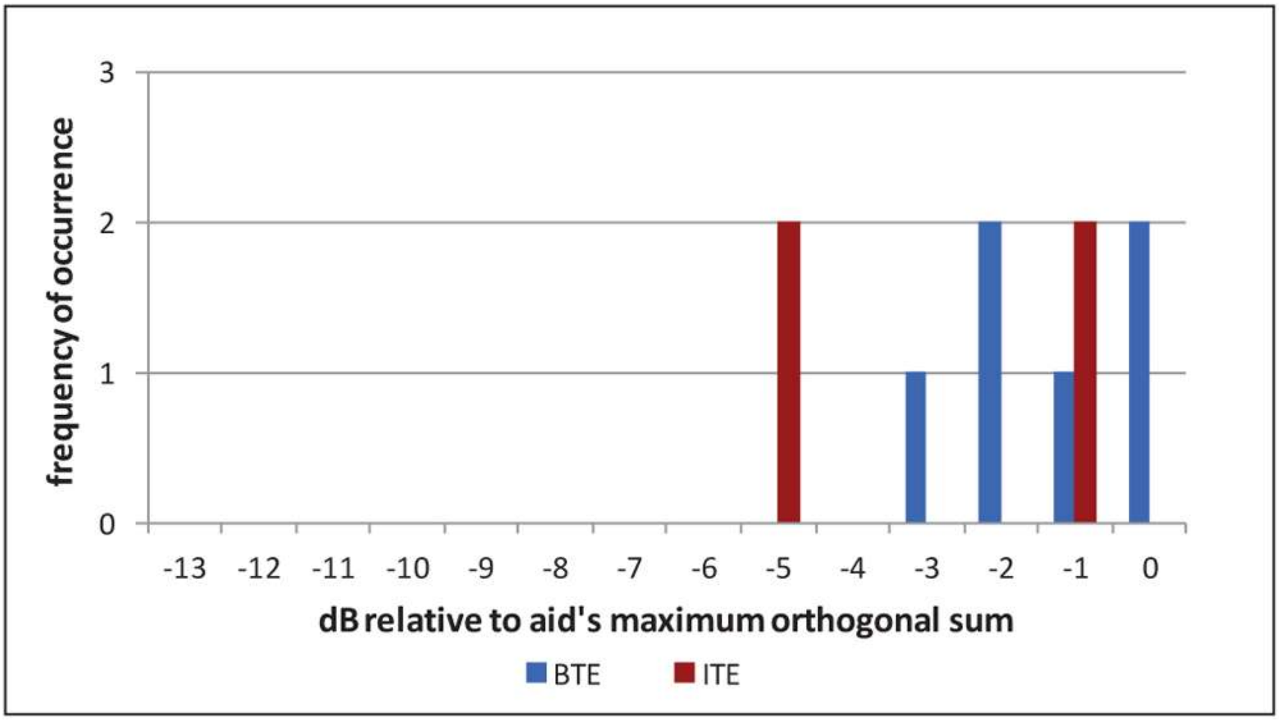

Fig. 9.

RF sensitivities of the 10 tested aids according to the rotation method of IEC 60118-13, the results normalized to each aid's maximum orthogonal sum.

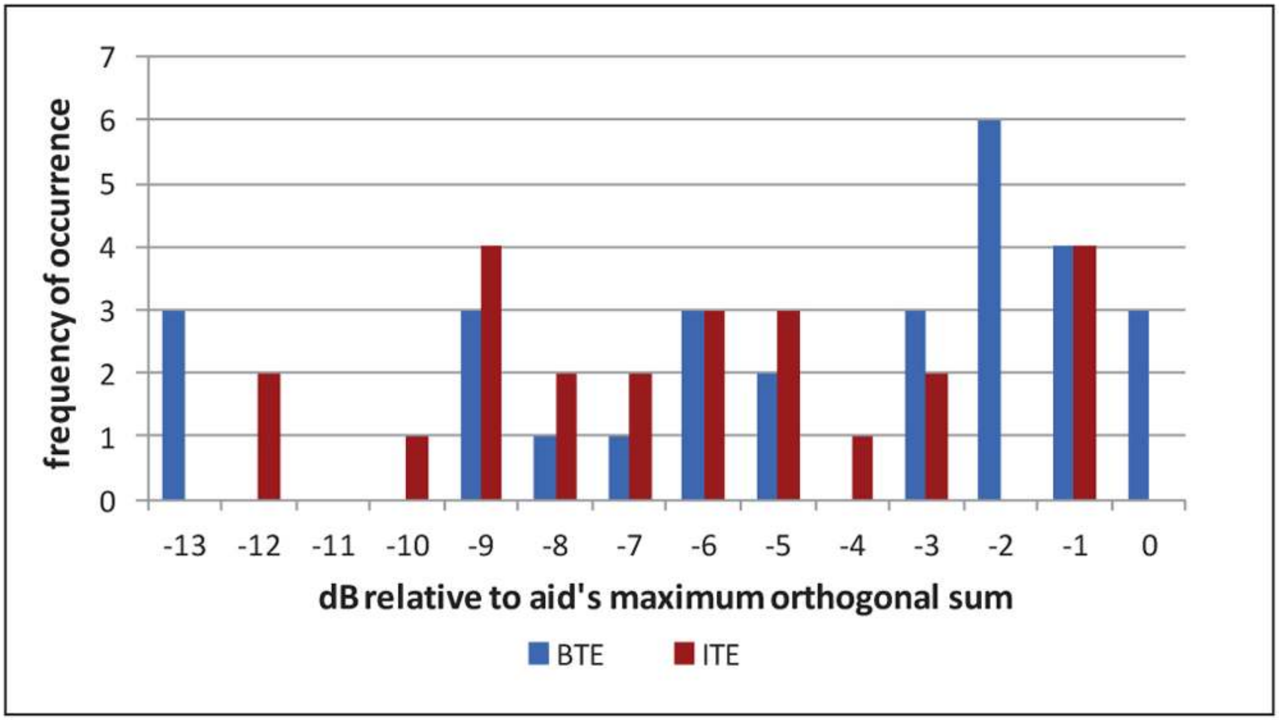

Fig. 10.

RF sensitivities of the 10 tested aids, calculated as in Fig. 9, but including all six unique cube orientation sequences, derived from the various initial orientations. (7 of the 6 × 6 BTE results have all four contributing measurements in the noise floor and are not plotted.)

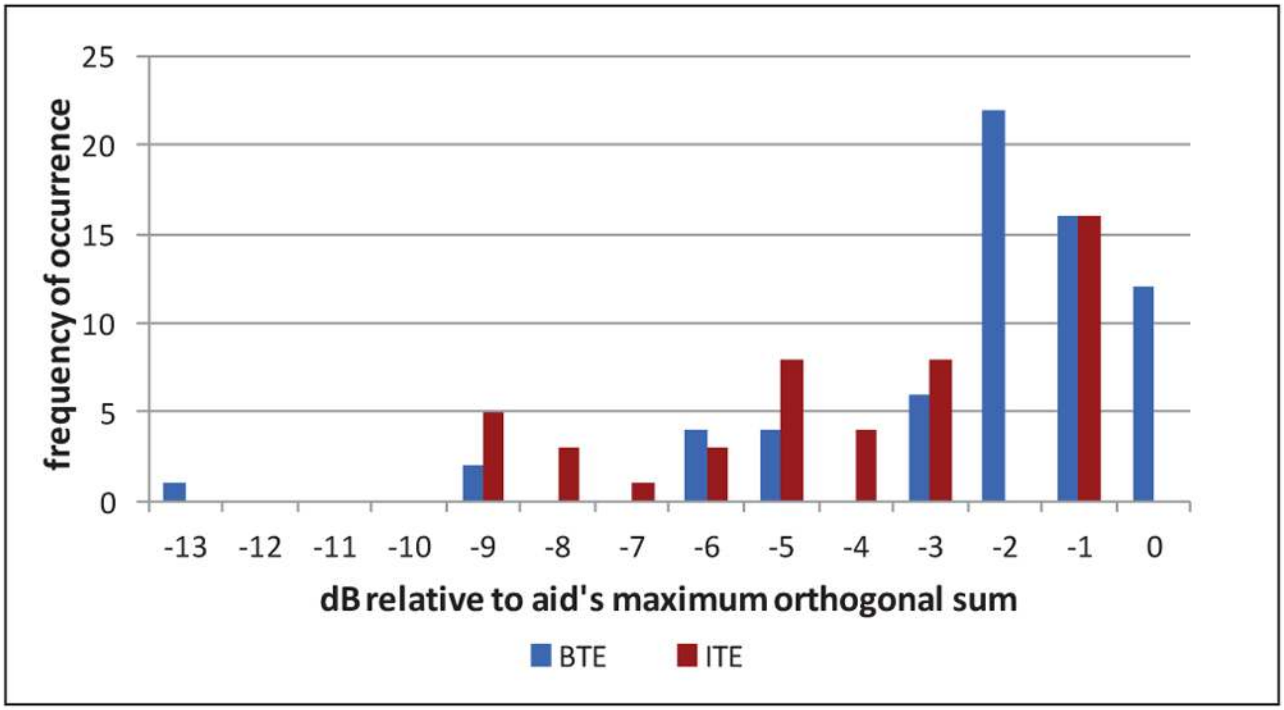

Fig. 11.

RF sensitivities of the 10 tested aids, calculated from a 90° approximation to the continuous rotations of C63.19, using the appropriate 12 unique pairs of the rotation sequences of Fig 10. (5 of the 12 × 6 BTE results have all four contributing measurements of both of the paired sequences in the noise floor and are not plotted.)

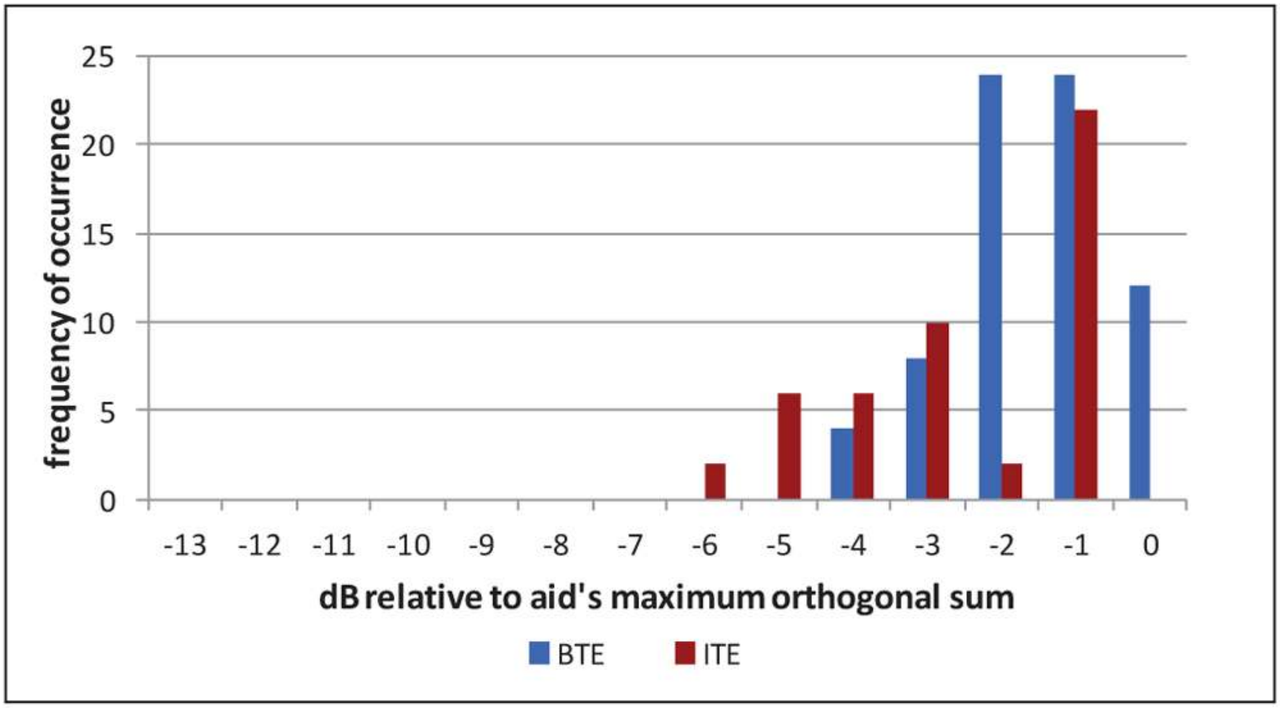

Fig. 12.
RF sensitivities of the 10 tested aids measured according to the 8-measurement immunity test of IEC 61000-4-20, using all 12 unique cube rotation sequences.

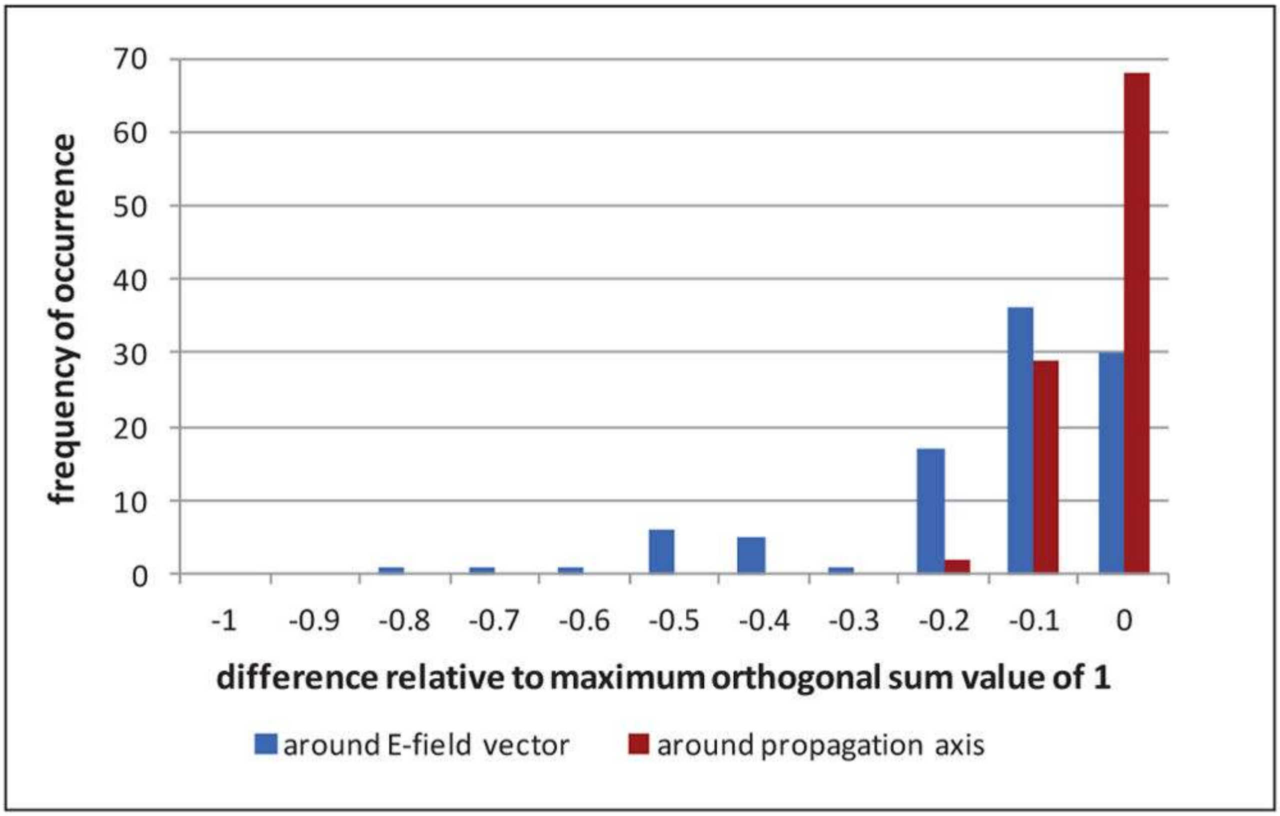

Fig. 13.

Differences between paired 180°-rotated measurements (after square law detection, normalized to a maximum orthogonal sum value of 1).

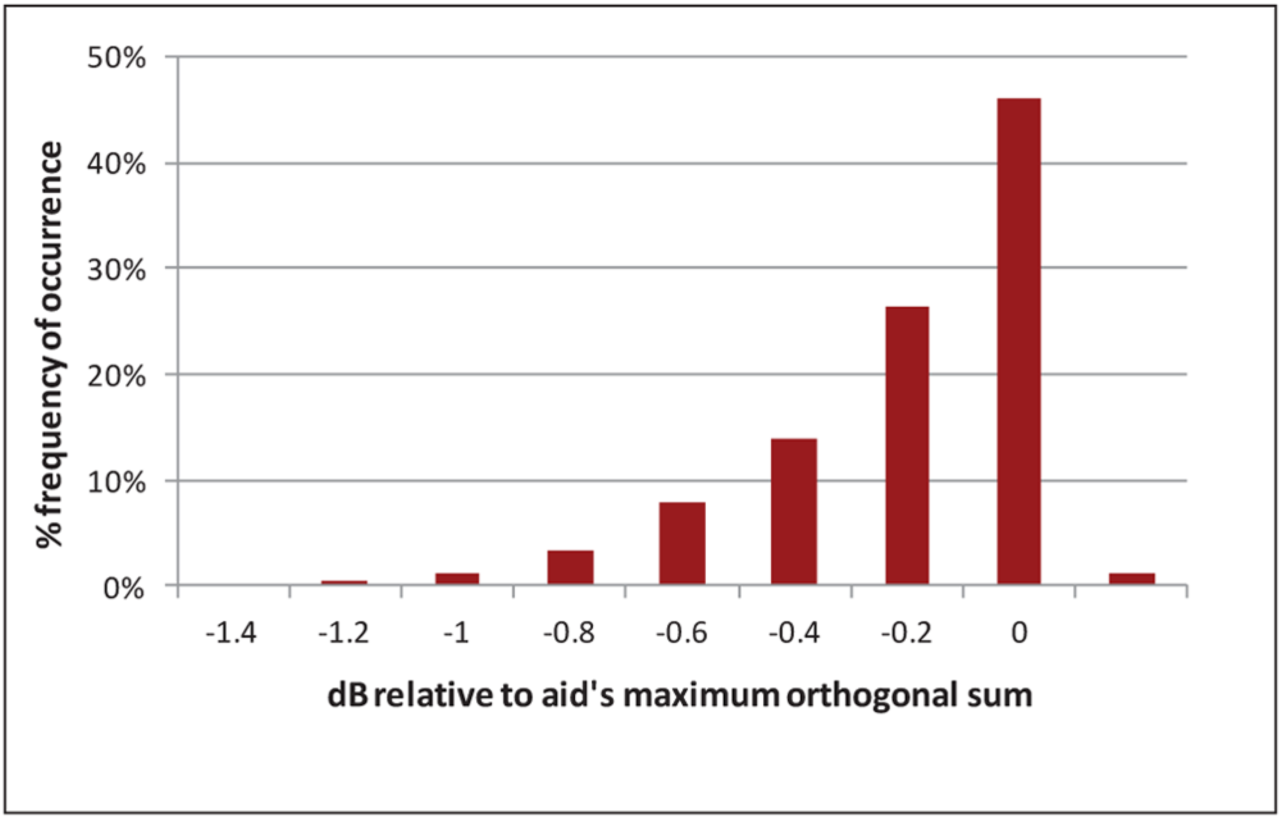

Fig. 14.
Maxima of the 4096 possible odd-even maximal sum pairings relative to the maximum of the 32 orthogonal sums, for each of the 10 aids tested.

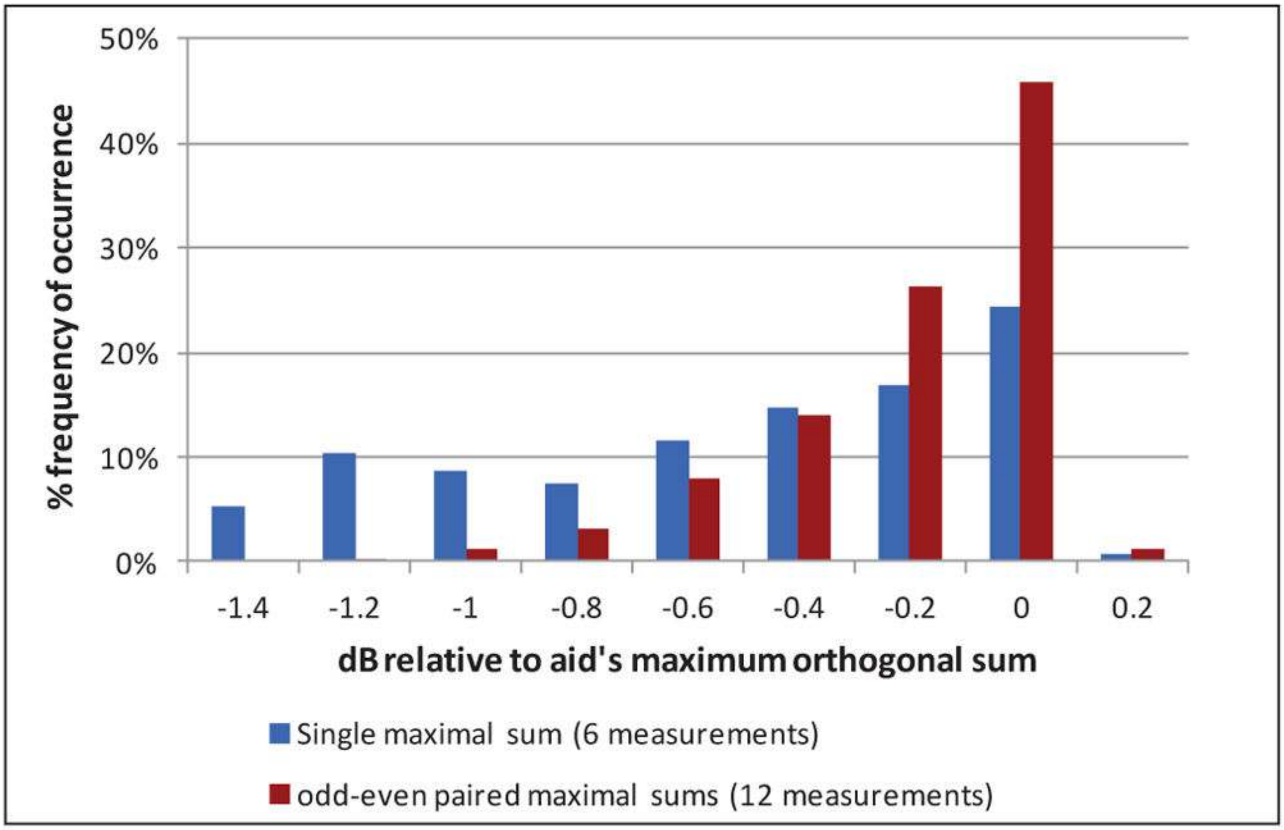

Fig. 15.

Individual 6-measurement odd and even maximal sum results (128 total for each of 10 aids) compared to the 12-measurement-based results of Fig. 14.

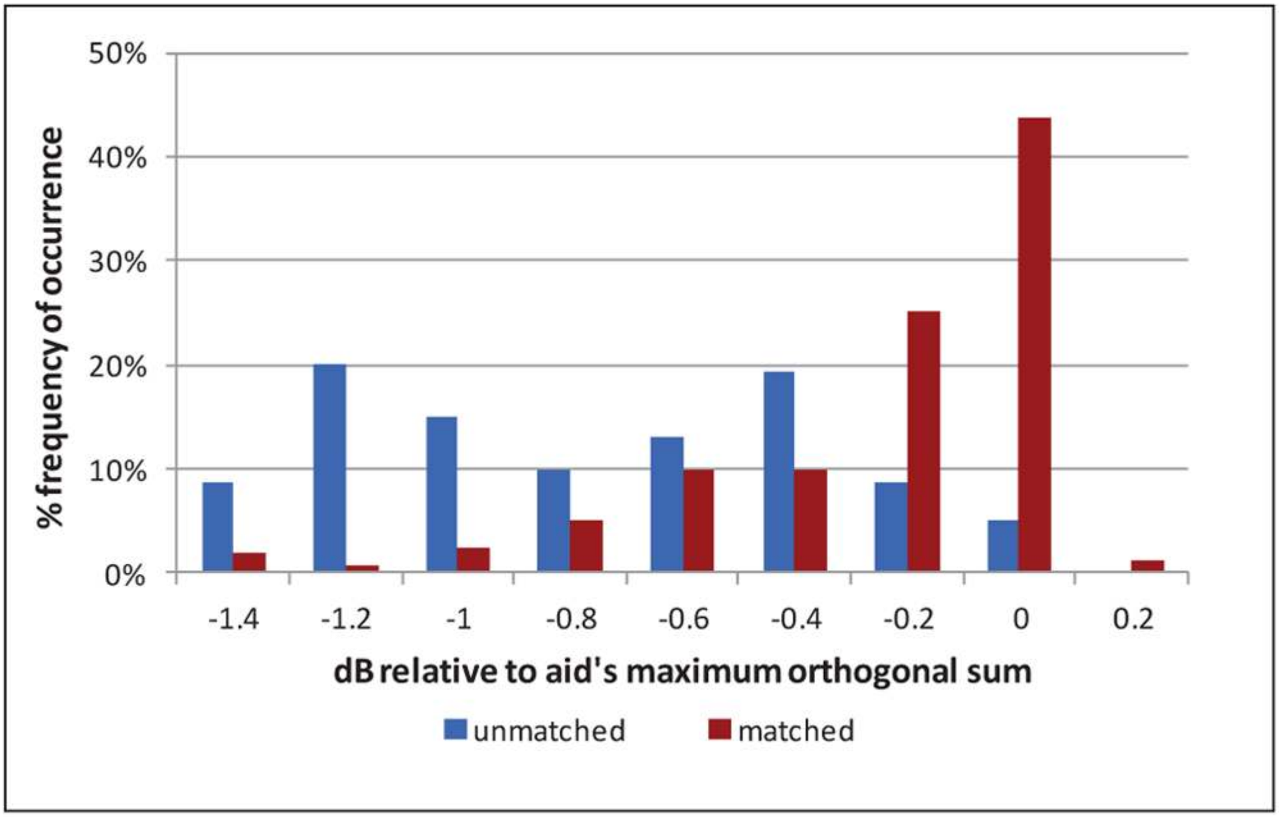

Fig. 16.
The single maximal sum data of Fig. 15, but with the “matched” and “unmatched” conditions separated.

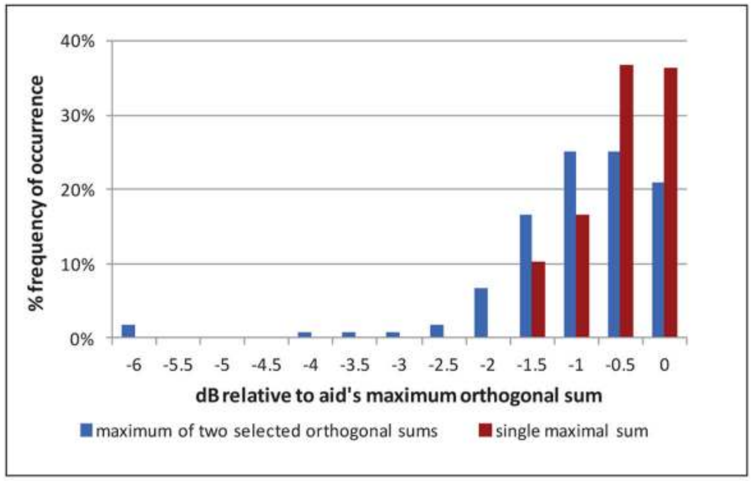

Fig. 17.

Results from an immunity calculation modeled after the 6-orientation small EUT emissions test of IEC 61000-4-20 (12 × 10 data points), compared to the 6-measurement maximal sum results of Fig. 11 and 12 (128 × 10 data points).

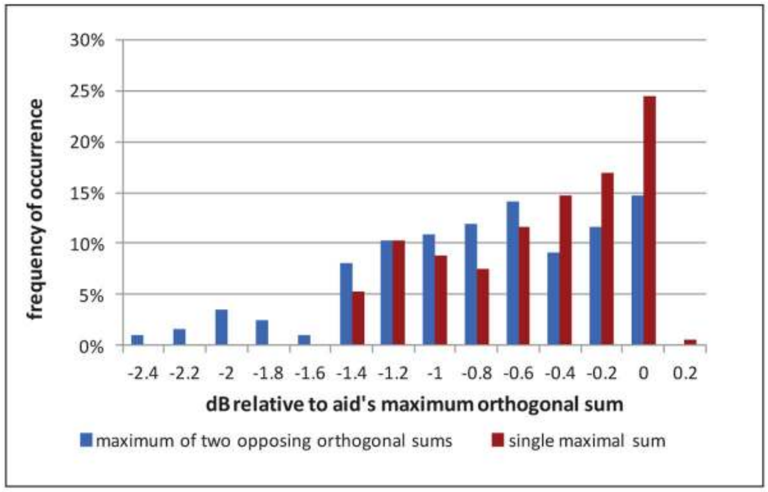

Fig. 18.

A similar comparison as in Fig. 17, except that the selection of the maximum of two orthogonal sums is now between two opposing orthogonal rotations, addressing all six faces (32 × 10 data points).

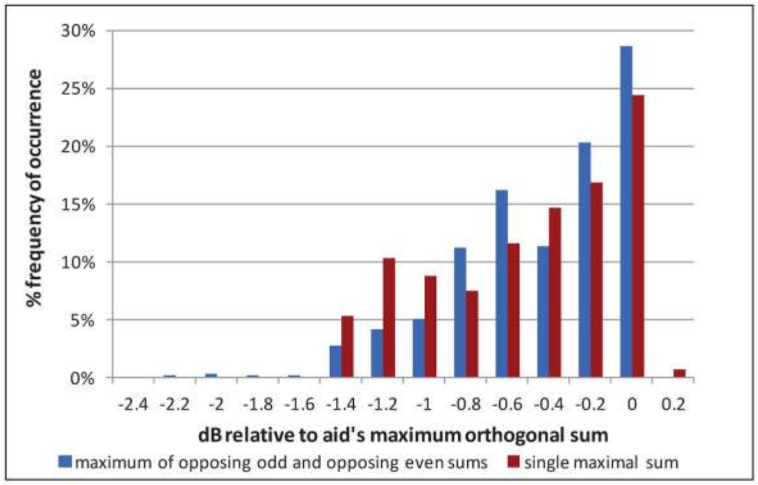

Fig. 19.

The highest of opposing odd and opposing even orthogonal sum pairs, addressing both polarizations of each face (12 contributing measurements; 256 × 10 data points), compared to 6-measurement maximal sum results.

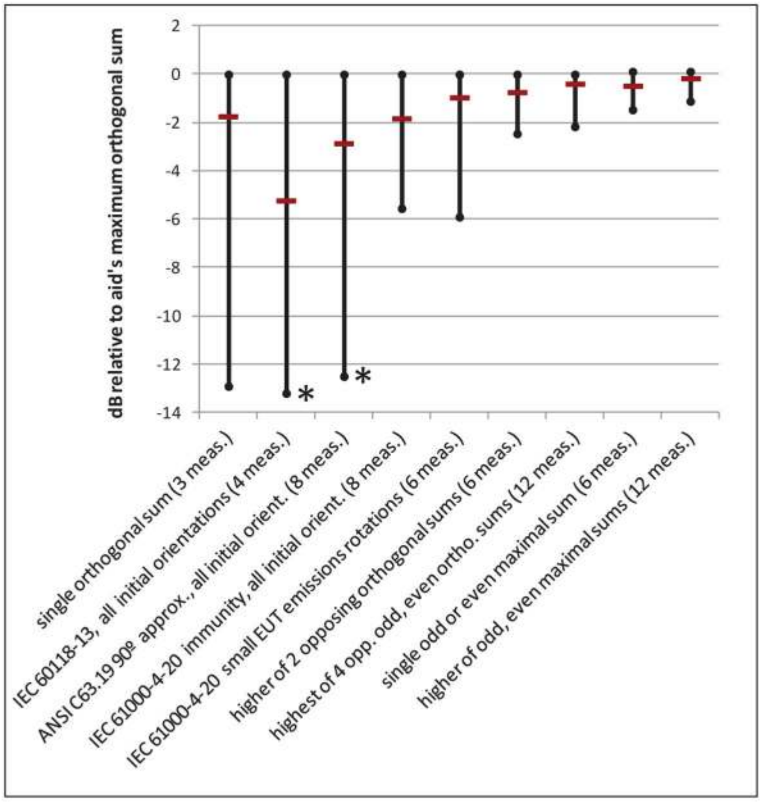

Fig. 20.

The ranges and means of the calculated RF sensitivity results for each of the discussed measurement approaches for the 10 tested hearing aids over the range of possible EUT starting orientations, as compared to the common reference of each aid's maximum orthogonal sum. (*Measurements in the noise floor are not included.)

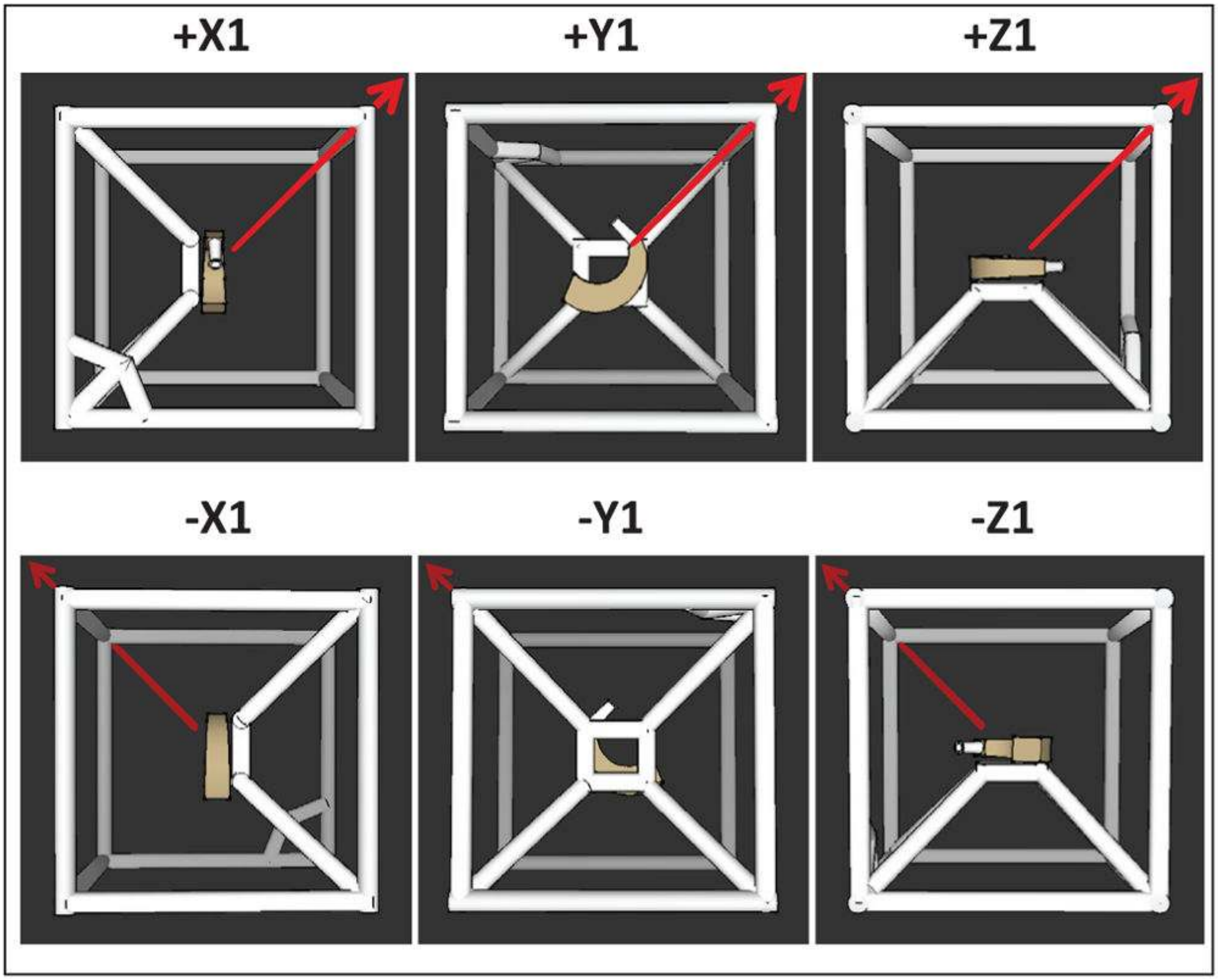

Fig. 21.

As viewed from the RF source, the three mutually orthogonal orientations +X1, +Y1, +Z1 of Fig. 6 paired with their opposing orientations, completing a maximal sum measurement set. The ortho-axis of rotation for the set of −X1, −Y1, −Z1 extends from the lower-right-front to the upper-left-rear, as viewed from the RF source.

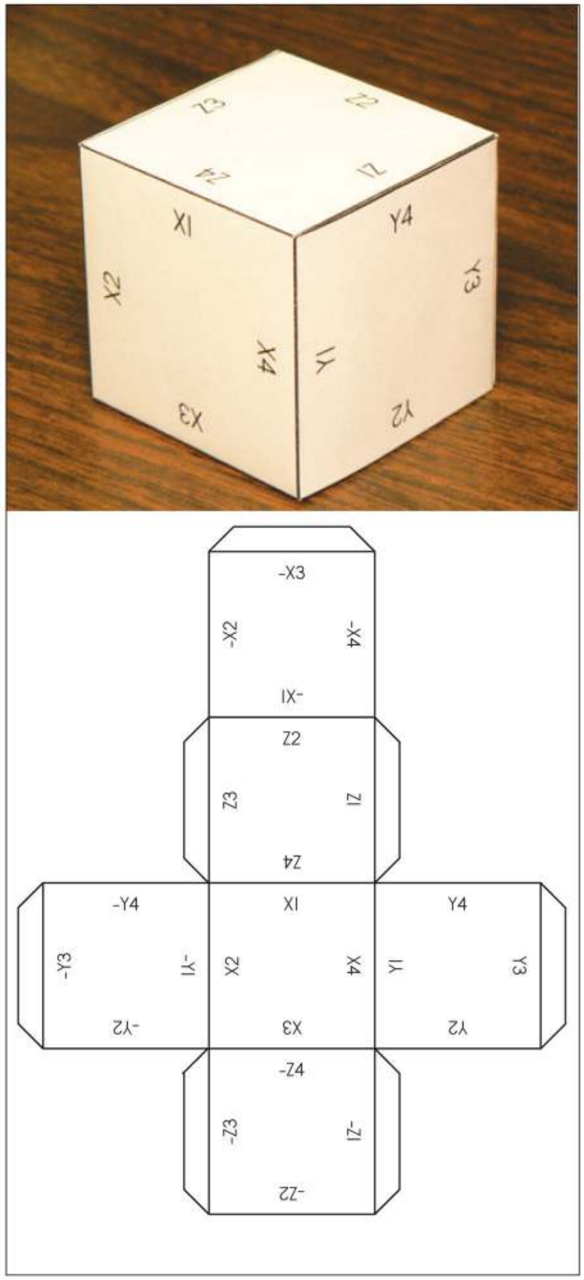

Fig. 22.

To aid in visualization, a construction template and finished cube showing the EUT orientation labeling.