*Sputtered Silver & Electroless Nickel*

Table 4 shows the improvements observed with sputtered silver, using four thicknesses on the inside of the plastic case parts of the test hearing aid and using a coating of electroless nickel deposited on all sides of the two case halves. The same hearing aid (printed circuit board and transducers) was mounted in each sample of case parts in succession and the aid measured for correct operation. It was thought that films comparable with the skin depth of 2.15 µm might provide less shielding, but this was not found to be the case. The results are quite variable since the silver did not adhere well to the case sides thus it did not provide a complete shield. It was concluded that the thickness was not as important as a continuous electrically conductive coating. The electroless nickel was coated on all surfaces of the case parts by electro-deposition and gave similar results. Typical improvements of about 16 dB were obtained with the sputtered silver and nickel shielding. No measurements were made with telecoil input.

**Table 4 Electrostatically Shielded with Sputtered Silver & Nickel, Microphone Input**

| *Hearing Aid* | | | | | *Immunity Level ILM40 (dB re 1 V/m)* | | |
|---|---|---|---|---|---|---|---|
| *Type* | *Manufacturer* | *Model* | *Treatment* | *Thickness in microns* | *No Shielding* | *With Shielding* | *Improvement* |
| MP BTE | Calaid | VHK | Sputtered Silver§ | 1 | -4.8† | 11.3 | **16.1** |
| | | | | 2 | | 12.2 | **17.0** |
| | | | | 3 | | 13.0 | **17.8** |
| | | | | 5 | | 8.4 | **13.2** |
| | | | Electroless Nickel | na | | 17.3 | **22.1** |
| MP BTE | Oticon | 425 | Decorative | ‡ | 10.5 | 23.0 | **12.5** |

§ These coatings tended to flake off and did not completely coat the surfaces treated.
† The same amplifier and transducers were used in these tests.
‡ Case sides coated on outside with an electroplated 3 to 5 micron Nickel-Tin over 3 to 5 micron Copper.

## Metal Impregnated Cases

Three samples of material were tested. Very fine stainless steel filaments were mixed in the plastic resin used to mould the cases of two types of BTE hearing aids. The material used was:

Type 1 ABS compound with 1.5% by volume of Beki-Shield®, fibre length 5 mm, diameter 8 µm, compounded by the manufacturers.

Type 2 Same as Type 1, but was compounded locally with some carbon content.

Type 3 Material moulded in Switzerland with same material as type 1.

Table 5 and Table 6 give the observed results, which show a useful improvement between 10 and 17 dB using the Type 1 material compounded by the manufacturer. It was suspected that the metal filling of Type 2 material was damaged during compounding.

**Table 5 Shielded with Metal Impregnated Case Mouldings, Microphone Input**

| *Hearing Aid* | | | | *Immunity Level ILM40 (dB re 1 V/m)* | | |
|---|---|---|---|---|---|---|
| *Type* | *Manufacturer* | *Model* | *Treatment* | *Unfilled Case* | *Filled Case* | *Improvement* |
| MP BTE | Calaid | VHK | Type 1 | -0.9 | 9.7 | **10.6** |
| | | | | -2.2 | 15.4 | **17.6** |
| | | | Type 2 | -0.9 | -4.7 | **-3.8** |
| | | | | -2.2 | -4.2 | **-2.0** |
| HP BTE | Phonak | PPCL4 | Type 3 | 7.8§ | 9.4 | **1.6** |
| | | | | 7.8§ | 6.1 | **-1.7** |

§ This value is the average of a small sample of other hearing aids of the same type.

**Table 6 Shielded with Metal Impregnated Case Mouldings, Telecoil Input**

| *Hearing Aid* | | | | *Immunity Level ILT20 (dB re 1 V/m)* | | |
|---|---|---|---|---|---|---|
| *Type* | *Manufacturer* | *Model* | *Treatment* | *Unfilled Cases* | *Filled Cases* | *Improvement* |
| MP BTE | Calaid | VHK§ | Type 1 | 0.30 | 13.3 | **13.6** |
| | | | Type 2 | -0.30 | -1.09 | **-0.79** |

§ The same amplifier and transducers was used for these tests.

## Shunt Capacitors

During the project, the design of a new hearing aid B. ·nafon NAL) was in progress. Shunt capacitors were included in this design in the hope that they would increase immunity. The capacitors are placed at the input leads of the integrated circuit amplifier and at the end of wires connected to the audio input socket of the aid. They are connected so as to shunt the three microphone leads together at radio frequencies. The capacitors used were Vitramon "High Q" VJ0603Q680JXB-AB, 68 pF, chosen for their small size and low inductance and equivalent series resistance at 1000 MHz.

Table 7 shows the results for the following cases:

- All capacitors removed,
- All capacitors in place, and
- Pairs of capacitors removed.

**Table 7 Shunt Capacitors Fitted to a Hearing Aid, Microphone Input**

| *Hearing Aid* | | | *Immunity Level ILM40 (dB re 1 V/m)* | | | | |
|---|---|---|---|---|---|---|---|
| | | | *Placement of Capacitors* | | | | *Improvement with all capacitors in place (dB)* |
| *Type* | *Manufacturer* | *Model* | *None* | *Pair Near IC Input only* | *Pair Near Audio Input only* | *All* | |
| HP BTE | NAL Bernafon | SP675 | 9.9 | | 17.6 | 21.6 | **11.7** |
| | | | 5.7 | 17.5 | | 21.4 | **15.7** |
| | | | 5.0 | 11.1 | | 21.5 | **16.5** |
| | | | 6.1 | | 20.0 | 22.4 | **16.3** |

Installing all capacitors gave improvements in immunity of 11 to 17 dB.

Fitting only one capacitor in any position did not give any improvement, suggesting that the interference could enter by both the microphone input and its power supply. Removing pairs of capacitors from the input leads reduced the improvement.

## DISCUSSION

The hea aids were exposed to radio frequency fields inside a terminated wav gui aligned for maximum response. The maximum field strength used, 200 lt tre, was s cien o test f e maximum immunity required to cha te interferen All aring a displayed a square law response so that a si antity, called the *Immun Level* can be used to specify each response.

Hearing aids tested showed a wide range of susceptibility to interference from a one kilohertz amplitude modulated radio frequency signal at 900 MHz. *Immunity levels* varied in hearing aids (with and without treatment) from -9 to 50 dB re 1 volt per metre, i.e. the radio frequency field strength needed to produce the same response (40 dB SPL *equivalent input referred sound pressure*) in the individual hearing aids tested varied from 0.35 to 320 volts per metre.

Hearing aids (e.g. Bernafon NAL) designed with short wiring to the microphone gave significantly higher immunity compared with the older designs. The IT312 has about the minimum lead length possible.

By enclosing the hearing aids in an electrostatic shield, improvements in immunity from about 13 to over 30 dB in field strength were observed. Metal impregnated cases gave improvements of 10 and 17 dB for the Type 1 material and shunt capacitors were responsible for about 15 dB improvement. These improvements may be treated as independent. Given that these results showed a good improvement, further experiments with specially constructed amplifiers were not undertaken. Realistic modification of existing hearing aids was, in general not found to be possible.

## CONCLUSION

### Effect of the Treatments

Reducing lead lengths e.g. by "chip-on-board" construction techniques, produces the greatest reduction in interference and is a prerequisite for the application of other techniques.

Shielding was undertaken for these measurements by coating the outside of the hearing aids in most cases. Practical production methods need only to shield the amplifier and critical input wiring.

It was concluded that when the materials for metal impregnated cases are properly compounded, a useful improvement results. However, considering the moulding difficulty, especially for custom earmoulds used in In-the-Ear hearing aids, it does not seem to be an attractive design solution for reducing interference.

Shunt capacitors proved to be effective. The positioning and number of capacitors is important.

The large immunity of the SB13 hearing aid when used with the telecoil is attributed largely to the particular operation of the input circuit.

## Design for Increased Immunity

A very high level of immunity can be designed into hearing aids. Four effective means for increasing immunity in hearing aids were demonstrated. In order of effectiveness they are:

- Reduce the lead lengths in the hearing aid, i.e. reduce the physical size of the wires serving as the "effective antenna" in which radio frequency voltages are induced by the incident radio waves.
- Surround the amplifier with an electrostatic shield.
- Use shunt capacitors effective at the radio frequencies involved, to reduce the radio frequency voltages across the amplifier input transistors.
- Impregnate the plastic case parts with special stainless steel wire filler.

In addition, it is possible that immunity can be obtained through special circuit design.

Production prototype hearing aids must be measured during the development of new hearing aids to ensure that the desired immunity is achieved in manufacture. The terminated waveguide provides a convenient tool to test hearing aids during their development phase.

# 3. Subjective Measurement of Hearing Aids

Subjective measurements were made of the GSM interference experienced when hearing aids were worn by hearing-impaired people (Part A) and by persons with normal hearing (Part B). The measurements determined the distance at which interference was detectable and/or annoying. From Part A it was concluded that some hearing aid models, but not others, could be used within one metre of a mobile telephone. One model also permitted some (not all) wearers to use a *hand-held mobile phone*. Part B, undertaken after completion of the technical measurements of untreated and treated hearing aids, helped to determine the relationship between immunity levels and the degree of interference experienced by a hearing aid wearer. The information is used to suggest bounds for immunity levels to incorporate in hearing aid design Standards.

## NEED FOR SUBJECTIVE MEASUREMENTS

There are two reasons why subjective measurements were required for the present investigation.

First, when a hearing aid is worn the body provides some shielding which reduces the amount of interference that occurs relative to what will occur when the hearing aid is measured in free space. The effect of the body will vary from person to person and depends on the orientation of the hearing aid to the transmitting device (i.e. the GSM telephone). It is, therefore, necessary to measure interference on a number of people, and for various orientations, to obtain a realistic (average) estimate of what allowance should be made for the effect of the body when using technical measurements of interference to predict its effects on hearing aid wearers. It is necessary to make subjective measurements for various types of hearing aids because the shielding provided by the body may vary with hearing aid type (e.g. it may be different for in-the-ear models compared with behind-the-ear models).

Second, the extent to which interference is detectable, or annoying, will depend on how audible it is and this will depend on the hearing of the individual hearing aid wearer as well as the level of interference. It is necessary to establish detection or annoyance levels for hearing-impaired people with hearing losses of the degree for which each type of hearing aid is appropriate (i.e. for typical users of that type of hearing aid).

The second part of this chapter presents measurements for persons with normal hearing. This can be justified as representing a "worst case" situation. It can be assumed that if no interference is detectable by a person with normal hearing, then none will be detectable by a person with a hearing loss. Of course, **some**

hearing-impaired people may not detect interference that is detectable by persons with normal hearing. However, a substantial number of hearing aid wearers have normal or near normal hearing at some frequencies (usually the low frequencies) and could be expected to detect interference at levels that are just detectable by a person with normal hearing. Therefore, if a single immunity standard is to be used for all hearing aids, it is appropriate to base this on the detectability of interference by listeners with normal hearing. Such a standard might, however, be unnecessarily stringent for high-powered hearing aids which are usually only fitted to people who have substantial hearing losses at all frequencies.

## PART A - HEARING IMPAIRED PERSONS

### METHODS

#### Subjects

Five groups of four to eight subjects each were used to test interference for five types of hearing aids. The subjects all had hearing losses of the appropriate degree for the type of aid being tested and all wore the hearing aids on the volume control setting preferred for listening to conversation in a quiet environment.

#### Hearing Aids

Two ITE models (Bernafon NAL IT312; Phonak 9000) and three BTE models (Bernafon NAL SB13, NAL VHK, Phonak PPCL4) were tested. These aid models were chosen to represent a wide range of immunity levels, as shown by technical measurements. (All except the Phonak 9000 had been measured before the subjective testing was conducted.) The IT312 is a recent model modular ITE with very compact circuitry and a very high immunity level. The Phonak 9000 is a somewhat older custom ITE, typical of many aids on the market. Because of the custom design, it has longer earphone and microphone leads than the IT312 and it was thought that this could make it more susceptible to interference. The SB13 is a recent model medium powered BTE with compact circuitry and good immunity. The PPCL4 is a high powered BTE which is current but has been available for several years. The VHK is a medium powered BTE (less powerful than the PPCL4) which had the least immunity of those tested initially (Joyner et al, 1993). It is a 10-year old model no longer currently issued by AHS but nonetheless still in service and of similar design to some other currently used hearing aids. This range of aids probably covers almost all degrees of interference that would be encountered in currently used hearing aids.

## TEST PROCEDURE

The test procedure was designed to determine how close the telephone could be to the hearing aid before any interference became detectable. Testing was performed in a large room with a four metre length of tape on the floor and marked at 0.3 metre intervals. The subject was seated on a chair at one end of the tape and the tester, operating the telephone, approached from the other end. At the beginning of the test and, if necessary during the test, the tester dialled a recorded message. The subject, with eyes closed, was instructed to raise his or her hand when he or she could hear interference (a "buzz") and lower the hand when the buzz was gone. (Before the test, the nature of the interference had been demonstrated by holding the telephone close enough to the hearing aid that the buzz was clearly audible.) Starting at a distance of 4 metre, the tester (an audiologist) moved slowly towards or away from the subject to establish the maximum distance at which the interference could be consistently detected. The procedure was analogous to the combined ascending/descending approach used in audiometry and was repeated as often as needed to get a reliable result. The telephone was held as it would be used for making a call. Most testing was conducted for four orientations: subject facing the tester; subject's back to tester; aided ear to tester, unaided ear to tester. (Only one hearing aid was worn during the test, even if the subject normally used a bilateral fitting.) For the final round of testing, the Phonak 9000, only the "aided ear to tester" orientation was used.

It was also established whether interference would prevent the subject from using the hand-held digital telephone.

The hearing aids were tested for microphone and telecoil use except for the 9000 model which does not have a telecoil. The PPCL4 was also tested with a metal-impregnated case. The VHK was tested with a silver loaded paint case and, for two subjects, with a metal-impregnated case also.

An additional test was performed with the Phonak 9000 ITE, which was evaluated several months later than any of the other aids. The subjects were asked to rate how annoying the interference was at distances of 1 metre and 0.7 metre.

## RESULTS

### In-The-Ear Hearing Aids

*Bernafon NAL IT312* (ILM40 ≈ 30 unmodified)

In early October 1993, five mild to moderately hearing-impaired clients were tested with standard and with modified Bernafon NAL IT312 (ITE) hearing aids. (The modification was the addition of capacitors, a method which technical measurements had shown to increase immunity.) For a hand-held GSM telephone, there was **no** interference for microphone listening even with the standard hearing aid. A client could use this type of telephone provided it could be held against, or close to, the hearing aid without incurring acoustic feedback. Some clients could use the telephone satisfactorily but others needed to hold it away from the ear and were then unable to hear adequately. This telephone could not be used for telecoil listening because a "buzz" occurred when the telephone was about 0.3 metre from the aid. This interference was noted only when the hearing aid was switched to telecoil.[10] (It is thought that this type of interference could vary depending on the particular type of GSM handset but no other telephones were available for testing at that time.) It was possible to use, on microphone or telecoil, a transportable GSM telephone in which the *handset* was separated from a *transceiver*.

It was concluded that there is **no need** to modify the IT312 or similar high-immunity hearing aids to avoid interference from other people's use of GSM *mobile telephones*. When these aids are worn, immunity increases to the point where there is little possibility of interference. Access to *hand-held mobile telephones* is available to some IT312, or similar, hearing aid users (on microphone), but others would need to use a model in which the *handset* is separated from the *transceiver* during use. Further investigation is required to determine the best way to provide access to *hand-held digital telephones* for all users of this type of hearing aid.

*Phonak 9000 ITE* (ILM40 ≈ 19 unmodified,)

In May and July 1994, four mild to moderately hearing-impaired listeners were tested with Phonak 9000 custom ITE hearing aids. They were tested only in the "aided ear to tester" orientation as this had been found to produce the most interference (see below). The maximum distances at which interference was detectable by the four subjects were: 0.2, 0.4, 0.7, 0.8 metre. On a four point scale ("not annoying", "slightly annoying", "annoying", "very annoying"), the two subjects who could hear interference at 0.7 metre, rated it as "slightly annoying". (The

[10] The nature of this effect was not explained, but in previous tests this phenomena was not exhibited around the *handset* or *transceiver* of a transportable cellular mobile station. It was later observed with all hearing aids switched to telecoil.

other two subjects could not hear interference at 0.7 metre and no subject could hear interference at 1 metre.)

### Behind-The-Ear Hearing Aids

During the period 30 November to 3 December 1993, immunity treatments to BTE aids were evaluated with moderately and severely hearing-impaired subjects. Testing was conducted for four hearing aid/telephone orientations: (subject facing the telephone; telephone directly behind subject; subject's unaided ear towards telephone; subject's aided ear towards telephone). With a few minor exceptions, this last condition ("sideways direct") produced the most interference. All of the following values refer to the minimum distance at which interference was detected in this "worst case" condition.

*Phonak PPCL4 high-power BTE* (ILM40 ≈ 8 unmodified, ≈ 9 treated)

Hearing aids with untreated and treated (metal impregnated) cases were evaluated on 8 subjects for microphone input and 7 subjects for telecoil. For microphone, untreated values ranged from 0.3 to 4+ metre, average = **1.43** metre. Treated values ranged from 0 to 1.0 metre, average = **0.33** metre. For telecoil, untreated values ranged from 0 to 1.2 metre, average = **0.39** metre. Treated values ranged from 0 to 0.3 metre, average = **0.11** metre.

*Calaid VHK medium-power BTE* (ILM40 ≈ -3 unmodified, 22 treated)

Hearing aids with untreated and treated (coated with silver loaded paint) cases were evaluated on 8 subjects for microphone and 7 subjects for telecoil. For microphone, untreated values ranged from 0.3 to 4.+ metre, average = **3.2** metre. Treated values were from 0 to 0.6 metre, average = **0.25** metre. For telecoil, untreated values were 0.1 to 0.4+ metre, average = **0.26** metre. Treated values were 0 to 0.4 metre, average = **0.17** metre.

Two subjects were also tested with VHKs with metal impregnated cases. For one subject, microphone results were: untreated = 4.0 metre, coated = 0.4 metre, metallised coating = 0.5 metre. Corresponding values for coil were: 0.36, 0.4, 1.0 metre. For the other subject, microphone results were: untreated = 1.8 metre, coated = 0.1 metre, metallised = 0 metre. Corresponding values for coil were: 1.2, 0.1, 0 metre.

*Bernafon NAL SB13 medium power BTE* (ILM40 ≈ 15 )

The SB 13 BTE hearing aid was tested untreated on 8 subjects. Values ranged from 0 to 0.2 metre for microphone and telecoil.

## Summary

Subjective results for hearing impaired persons are summarised for microphone input in Table 8.

**Table 8 Nearest Distances (from *Mobile Telephone*) of Perceived Interference**

| *Hearing Aid* | | | | | *Distance at which Interference was Apparent* | |
|---|---|---|---|---|---|---|
| *Type* | *Manufacturer* | *Model* | *Treatment* | *Approximate ILM40 (dB re 1 V/m)§* | *Distance from Mobile Telephone (metres)* | *Average Distance (metres)* |
| ITE | Bernafon NAL | IT312 | None | 30 | No interference against hearing aid, both treatments | 0 |
| | | | Added Capacitors | > 30 | | |
| | Phonak | 9000 | None | 19 | 0.2 to 0.8 | 0.5 |
| BTE | Bernafon NAL | SB13 | None | 15 | 0 to 0.2 | - |
| | Calaid | VHK | None | -3 | 0.3 to 4.0 | 3.21 |
| | | | Silver Paint | 22 | 0 to 0.6 | 0.25 |
| | | | Metal Impregnated Case | 10 | 0 to 0.5 | - |
| HPBTE | Phonak | PPCL4 | None | 8 † | 0.3 to 4.0 | 1.43 |
| | | | Metal Impregnated Case | 9 | 0 to 1.0 | 0.33 |

§ These values are estimated from subsequent tests when the equipment was available.
† This is the average of similar hearing aids.

## Access

Most subjects were tested to see whether they could use the telephone (a hand held model) with the above BTE aids. None could do so satisfactorily. (Even subjects who had detected no interference at 0 metre distance, did receive an unacceptable "buzz" when the telephone was re-oriented for telephone use.)

## CONCLUSIONS

### In-the-Ear Hearing Aids

These results (for four subjects only) suggest that users of this type of aid are unlikely to experience interference from other people's use of GSM telephones. However, the possibility cannot be entirely excluded as there may be other aid wearers who can detect interference at greater distances than any of our subjects and they could come within 1 metre of a telephone user in some situations (e.g. on public transport).

### Behind-the-Ear Hearing Aids

Both the coating with silver loaded paint and the metal impregnated case treatments have been effective in substantially increasing the immunity of BTE hearing aids when they are worn. For the Phonak and VLKs, the treatment reduced the interference distance to under one metre in all except one case (1 metre) and to under half a metre for most cases. From subjective measurements the SB13 appears to have high immunity and should not require treatment to avoid interference from other people's telephone use. However, none of these aids, treated or otherwise, provide access to hand-held *digital mobile telephones*.

## PART B - PERSONS WITH NORMAL HEARING

### MODIFIED HEARING AIDS

When the physical measurements were completed, hearing aids that spanned the range of immunity levels of interest were available. During December 1994 another series of subjective testing was carried out using this expanded range of hearing aids. Simple listening tests were undertaken in an attempt to specify appropriate immunity levels that would be useful for hearing aid design. Two *classes* of use were considered:

- *Class 1*: a hearing aid used 1 metre distant from a transmitting *mobile telephone* was considered to be representative of the smallest distance that is likely to occur when *mobile telephones* are used in the vicinity of hearing aids, and
- *Class 2*: a hearing aid used to communicate using a hand held *mobile telephone*.

### METHOD

A subjective assessment was made to determine the interference apparent for the two *classes* of use. People with normal hearing listened to the output of hearing aids with known *immunity levels* in the presence of a *mobile telephone*. The location of the test was selected to be in a low signal area so that the *mobile telephone* would be transmitting at or near maximum power.

### TEST PROCEDURE

#### Listening Tests

Two persons with normal hearing listened to the output of each hearing aid in one or more of the following manners:

- through a short length of 2 mm dia Tygon© tubing and a "Stethoclip© [11]",
- through a short tube using earmoulds to seal the output of BTEs into the ear,

[11] This is a device for conducting sound through small tubes to both ears.

- using "Bluetac"© to seal the ITEs in the ear.

### Conditions

The aids were listened to while placed:

- close to a 2 Watt (Class 4) mobile telephone so as to hear the telephone acoustic output,
- at one metre away from the telephone, and up to several metres.

The aids were placed in a range of positions and attitudes that were likely to be encountered in practice. The volume control settings of each hearing aid varied, but the hearing aid internal noise could be heard in all cases so that low gain would not cause an erroneous result. The relative orientations of the *mobile telephone* and the hearing aids were adjusted for the worst case as much as possible.

### Assessment of the Level of Acoustic Interference

The acoustic level of interference was judged to be:

- "Not perceptible",
- "Just perceptible",
- "Moderately perceptible" or
- "Annoyingly perceptible".

The intention was to gain a "realistic" indication of the relationship between the immunity levels and the interference that could just be perceived.

### Assessment of Usability

For each condition the hearing aid was judged to be:

- "Usable" indicating that the hearing aid was usable under all conditions,
- "Sometimes Usable" indicating that it was usable under some circumstances but not all conditions, and
- "Unusable" indicating that the hearing aid was not usable under the stated conditions.

# RESULTS

## Perceived Interference

The results are presented in Table 9. It clearly shows the range of immunity levels that are appropriate for each class of use. Even though the judgements are approximate, they are consistent with the previous subjective measurements in Part A.

**Table 9 Perceived Interference Near a 2 Watt Mobile Telephone**

| *Hearing Aid* | | | | *Class of Use* ¶ ¤ | | | |
|---|---|---|---|---|---|---|---|
| | | | | *Class 1 Condition at 1 metre* | | *Class 2 Use with telephone* | |
| *Type* | | *Treatment* | *Immunity Level* † *ILM40 (dB re 1 V/m)* | *Acoustic Level (Interference)* | *Usability* | *Acoustic Level (Interference)* | *Usability* |
| ITE | IT312 | Coated with silver paint | 48 | Not Perceptible | Usable | Not Perceptible | Usable |
| HPBTE | SP675 | Coated with silver paint | 41 | Not Perceptible | Usable | Not Perceptible | Usable |
| MPBTE | SB13 | Coated with silver paint on all sides | 35 | Not Perceptible | Usable | Not Perceptible | Usable |
| HPBTE | PPCL4 | Coated with silver paint | 34 | Not Perceptible | Usable | Just Perceptible | Usable § |
| ITE | IT312 | Untreated | 28 | Not Perceptible | Usable | Moderately Perceptible | Sometimes Usable |
| MPBTE | 425 | Decorative plated case | 23 | Not Perceptible | Usable | Moderately Perceptible | Unusable |
| HPBTE | SP675 | Untreated (includes shunt capacitors as standard) | 22 | Not Perceptible | Usable | Annoyingly Perceptible | Unusable |
| MPBTE | VHK | Electroless nickel | 17 | Moderately Perceptible | Usable | Annoyingly Perceptible | Unusable |
| MPBTE | SB13 | Coated with silver paint on 3 sides | 16 | Not Perceptible | Usable | Annoyingly Perceptible | Unusable |
| MPBTE | SB13 | Untreated | 11 | Moderately Perceptible | Usable § | Annoyingly Perceptible | Unusable |
| HPBTE | PPCL4 | Metal impregnated case | 6 | Moderately Perceptible | Sometimes Usable ‡ | Annoyingly Perceptible | Unusable |
| MPBTE | VHK | Untreated | -3 | Annoyingly Perceptible | Unusable | Annoyingly Perceptible | Unusable |

¶ Condition at 1 metre (Class 1) - For hearing aids used in the vicinity of mobile telephones,
Use with telephone (Class 2) - For hearing aids used to communicate with mobile telephones.
¤ The tests were undertaken by two persons with normal hearing.
† This is the Immunity level (at 40 dB SPL acoustic input referred level) of the individual hearing aid used in each test. The corresponding immunity level can be calculated for any other acoustic (input referred) level. For example, should the field strength be required for 55 dB acoustic input then the immunity level (ILM) field strength would be increased by 15/2 = 7.5 dB. The corresponding RF field strength in volts per metre is calculated from the immunity level (ILM) by $E = 10^{(ILM/20)}$.
§ Indicates near limit of useability.
‡ In some directions the interference was just perceptible. Over a small angle it became annoying!

## CONCLUSION

Table 10 summarises the *immunity levels* which correspond to the subjective perceptions of persons with normal hearing listed in Table 9.

**Table 10 Hearing Aid Immunity Level - Summary**

| *Subjective Assessment* | | *Immunity Level ILM40 (dB re 1 V/m)* | |
|---|---|---|---|
| | | *At 1 metre* | *Use with Telephone* |
| *Level of Acoustic Interference* | Not perceptible | ≥ 22§ | ≥ 35 |
| | Just perceptible | - | 34 |
| | Moderately perceptible | 6 - 17 | 23 - 28 |
| | Annoyingly perceptible | ≤ -3 | ≤ 22 |
| *Usability* | Usable | ≥ 11 | ≥ 34 |
| | Sometimes Usable | 6 | ≈ 28 |
| | Unusable | ≤ -3 | ≤23 |

*§ One Hearing Aid with ILM40 = 16 has been omitted since the result appears to have been caused by selective shielding.*

This table suggests **lower bounds** on the *immunity levels* appropriate for design of hearing aids.

- Where **no interference** is allowed:
  - For use in the vicinity (≥ 1 metre) of transmitting mobile telephones: a bound between **17** and **22** dB re 1 V/m (**7** to **13** V/m) for 40 dB SPL equivalent input sound pressure,
  - For use with a mobile telephone: a bound about **35** dB (**58** V/m)
- Where **some interference** is allowed:
  - For use in the vicinity (≥ 1 metre) of transmitting mobile telephones: a bound about **11** dB (3.5 V/m)
  - For use with a mobile telephone: a bound between **28** and **34** dB (**25** to **50** V/m), however 28 dB was found to be only "sometimes usable".

As these values were found by persons with normal hearing, they are adequate for hearing impaired persons.

Given the uncertainty in the subjective measurements such as the exact conditions and the persons' hearing, the *immunity levels* quoted must not be treated as exact. Results varied greatly with orientation of the hearing aid relative to the *mobile telephone*, e.g. from the interference being just perceptible to being annoyingly perceptible. The bounds given must be treated with care, although they are believed to be realistic.

# 4. Development of Design Criteria

The purpose of the measurements has been to develop design criteria for immune hearing aids. Proposed design criteria are given in terms of *Immunity Levels* that would give acceptable communication for a hearing aid wearer in the vicinity of a *mobile telephone* and when hearing aids are used to communicate using *mobile telephones*.

## IMMUNITY

Immunity specifications for the design of hearing aids may be determined from the measurements described in the previous two chapters.

If hearing aids are to be considered "completely immune from this interference", then the interference will not be noticeable in any possible situation where the hearing aid can be used. In this case, the interference under worst case conditions would be considered to be acceptable only if it was sufficiently below the "noise floor"[12] of the hearing aid. However there are several considerations that allow this criterion to be relaxed and made more realistic.

From the hearing aid designers' perspective, a hearing aid should be designed to be as immune as technically possible, consistent with reasonable economy of manufacture and consumer satisfaction. This depends upon the current state of technical knowledge. It is clear from the measurements carried out in this study that hearing aids can be designed to be "immune" for all practical purposes, given sufficient development effort[13].

Radio frequency *signal strengths* to which hearing aids are exposed are considered next, followed by the amount of *acoustic interference* that may be tolerated. When the *Immunity Levels*, calculated for these conditions, are compared with the *Immunity Levels* suggested by the subjective test results, it is possible to propose realistic hearing aid immunity specifications.

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[12] This is the *equivalent input referred sound pressure* caused by the intrinsic internal noise of the microphone and amplifier of the hearing aid.

[13] While this effort is not trivial, the development effort needed to find suitable manufacturing techniques is not considered to be excessive for new designs.

The many *environmental and circumstantial variables* that apply in practice, act to reduce the perceived interference in any particular case. However, the proposed level of hearing aid immunity is still needed to cover the full range of circumstances.

## RADIO FREQUENCY SIGNAL STRENGTHS

### RF Field Strength around a Mobile Telephone

The signal strength that may be expected near a mobile telephone radiating at full power in a typical environment is shown in Figure 4 together with the theoretical value given by the formula:

$$E = k\frac{\sqrt{P}}{d} \tag{1}$$

where $E$ is the field strength in volts per metre, $P$ is the transmitted power in watts, $d$ is the distance from the antenna in metres and $k$ is a factor depending on the radiated field pattern and direction. This can only be an approximation since the field strength varies strongly with the environment, as indicated in Figure 4 for three cases. It is generally agreed that the field strength at one metre distant from a 2 watt GSM *mobile telephone* radiating at full power is between 3 and 10 volts per metre.

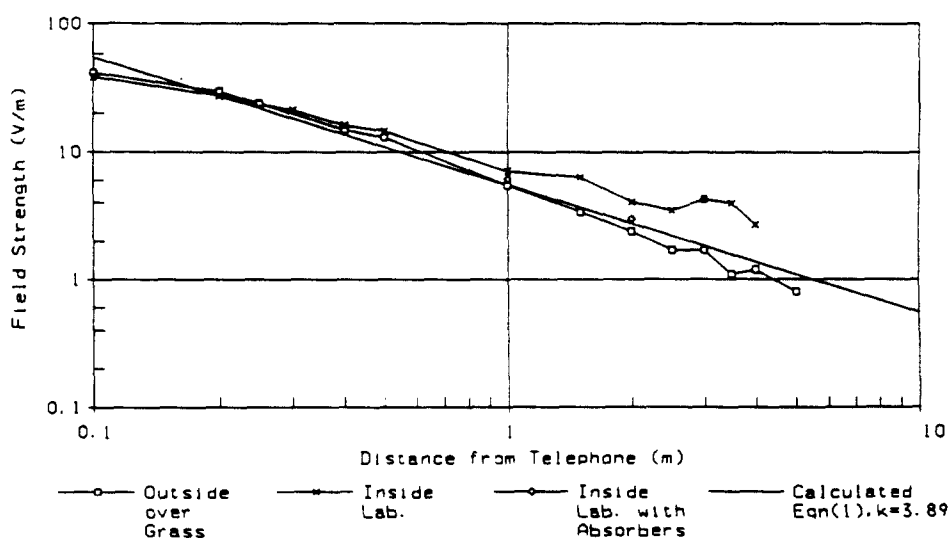


**Figure 4 Field Strengths near a 2 Watt (Class 4) Hand Held Mobile Telephone**

Source: Telecom Research Laboratories personal communication.

Closer than about 200 mm the field pattern around the telephone handset is complex, and the field strength may be greater than **40** V/m shown in Figure 4. It is thought from experience that **100** V/m or more is a realistic field strength to consider when a hearing aid is placed near the telephone receiver. Realistic measurements are not easy to carry out [5]. These field strengths are considered here since it is not planned to licence *hand-held digital mobile telephones* with a higher power in Australia.

### Relation Between Immunity Level and GSM Emissions

It is shown in Appendix 4 that in order to produce the same interference (detected input referred sound pressure) in a hearing aid, the field strength of the RF carrier of a GSM mobile telephone pulsed transmission must be greater than the carrier level used with the sinusoidal amplitude modulation by 10.2/2 = **5.1** dB. The actual spectrum of the interference in the hearing aid output depends on the filtering of the hearing aid amplifier.

## TOLERABLE LEVELS OF INTERFERENCE

### Measure of Interference

The interfering signal i.e. the *detected input referred sound pressure* and the microphone signal are effectively summed at the input of the hearing aid amplifier. The interference has frequency components with significant power over the whole useful frequency band of the hearing aid [1]. Given that the frequency response of each particular hearing aid is adjusted to make the best use of this input signal for the individual hearing impaired user, the *signal to noise* (interference) *ratio at* (or referred to) *the input* is the relevant quantity of interest. Hence criteria for acceptable levels of interference are given in terms of levels of the *detected input referred sound pressure.*

### Interference when using Telecoil

*Equivalence Between Microphone and Telecoil Sensitivities*

At the same audio frequency, a typical hearing aid may be expected to produce the same acoustic output in each of the following conditions:

- set to the *Telecoil* "T position" and subjected to a magnetic field of **20** dB re 1 milliamp per metre (i.e. 10 mA per metre),
- set to the *Microphone* "M position" and subjected to **50** dB SPL sound field.

*Relationship Between ILT20 and ILM40*

From Chapter 2, ILT20 is the radio frequency field strength that produces a response of 20 dB re 1 mA per metre *equivalent input referred magnetic field strength*. Also from Chapter 2, ILM40 is the radio field strength that produces a response in the hearing aid of 40 dB SPL *input referred sound pressure*.

For a hearing aid that meets the above specification, 20 dB re 1 mA per metre produces an acoustic response equivalent to 50 dB SPL *equivalent input referred sound pressure*.

Hence the ILM40 or *radio frequency field strength* to produce the same acoustic output as 40 dB SPL input sound pressure is (50-40)/2 = 5 dB lower than the ILT20 field strength (divide by 2 for square law detection). Thus the relationship between ILT20 and ILM40 can be expressed as:

$$ILT20 = ILM40 + 5 \qquad (2)$$

*Development of telecoil design criteria*

Further consideration of telecoil input is not needed for the development of design criteria since equation (2) may be used for the determination of the corresponding ILT20 for telecoil immunity. Note that equation (2) must be adjusted if a different equivalence between microphone and telecoil sensitivities is employed. Specifications and standards that use the *equivalent input referred magnetic field strength* must state the equivalence between microphone and telecoil sensitivities.

## Classes of Hearing Aid Immunity

As anticipated in Chapter 3, two classes of service are recognised as surrogates for practical situations:

Class 1 Hearing aids used one metre distant from a transmitting mobile telephone, i.e. in the vicinity of a mobile telephone, need to be immune from interference caused by other people using mobile telephones.

Class 2 Hearing aids used for communication using the mobile telephone, i.e. next to the receiver of the mobile telephone, would encounter very high field strengths.

Appropriate *Immunity Levels* for the two classes of application are considered using the field strengths discussed above:

- **3** and **10** volts per metre for Class 1, and
- **100** volts per metre for Class 2 service.

## Criteria for Acoustic Interference

The following levels of sound pressures are presented as suitable criteria from which an acceptable level of interference may be inferred.

*Minimum Perceptible Interference*

The hearing aid noise floor is dominated by the intrinsic microphone noise in well designed hearing aids. This is of the order of 23 to 28 dBA SPL. Interference with an *equivalent detected input referred sound pressure* of this level can be perceived in the hearing aid by listeners with normal hearing and by some hearing impaired listeners. At this level the interference is near the limit of "delectability".

*Hearing Aid Noise Criteria*

One third octave noise criteria developed for hearing aids [6][14] is equivalent to an A-weighted level of 33.7 dB SPL. Slightly modified [7], this criterion is used in specifying hearing aids manufactured for the Australian Hearing Services. Limiting interference to this level would ensure "good" or "acceptable" communication.

*Ambient Noise in Quiet Environments*

Pink noise at 35 dB SPL represents a quiet environment. Since hearing impaired persons have more difficulty hearing with increasing ambient noise, it would seem that noisier environments are not appropriate for setting specifications. This is considered to be a maximum of interference that is appropriate for specifying "immunity".

*Unacceptable Interference*

At about 20 dB above the hearing aid noise criteria (33.7) dB i.e. about **55** dB SPL, it has been observed (by the authors) that the interference is loud enough to be considered "unacceptable". Although this is an arbitrary level it gives an upper bound at which the interference is clearly undesirable.

## Calculation of Required Immunity Levels

Given the *radio frequency field strengths, E of a GSM transmission* to which the hearing aid can be exposed, and the *equivalent detected input referred sound pressures P* equal to the tolerable sound pressure levels discussed above, the corresponding *Immunity Levels* shown in Table 11 are calculated using:

$$ILM40 = E - \frac{10.2}{2} + \frac{40 - P}{2} = E + 14.9 - \frac{P}{2}, \qquad (3)$$

[14] The "Maximum equivalent input noise (measured in third octave levels) deemed to be acceptable when listening to a speech signal with a long term rms level of 65 dB SPL ...", is derived from an estimate of the signal to noise ratio in one third octave bands at 1 and 2 kHz considered to be "just acceptable" by a specially selected group of listeners.

where $E$ is the GSM radio frequency field strength in dB re 1 volt per metre and $P$ is the sound pressure in dB SPL. The term **10.2** corrects for the sinusoidal modulation used to define and measure ILM40. For example, consider a hearing aid that when exposed to a field **E = 100** volts per metre from a *mobile telephone*, its response i.e. the *equivalent detected input referred sound pressures* is **P = 34** dB SPL. The calculation, equation (3), for the *immunity level* of this hearing aid is illustrated in the following steps:

- The field strength E is 20 log(**100**) = **40** dB re 1 volt per metre.
- The field strength used for measuring the ILM40 is **10.2**/2 dB less, or **40** - 5.1 = **34.9** dB re 1 volt per metre.
- In order to give 40 dB SPL the field strength must be increased by the difference between 40 and P (= **34**) divided by 2 or (40 - **34**)/2 = 3.0 to give **34.9** + 3.0 = **37.9**, which is the **ILM40** shown in Table 11.

Note that the changes in sound pressure levels are divided by 2 to convert to changes in field strength, i.e. we have square law detection.

**Table 11 Immunity Levels for Interference Criteria**

| *Interference Level* | | ***Field Strength E*** § *of a GSM Interrupted Carrier Signal* | | | |
|---|---|---|---|---|---|
| | | *(Volts per metre)* | *3.0* | *10.0* | *100* |
| | | *(dB re 1 volt per metre)* | *9.5* | *20.0* | *40.0* |
| ***Criterion*** | ***Reference Sound Pressure P*** § *(dB SPL)* | ***Immunity Levels*** § *(ILM40 in dB re 1 volt per metre) of a hearing aid for each* ***Reference Sound Pressure and Field Strength*** | | | |
| A Weighted Microphone Noise | *23* | | 12.9 | 23.4 | 43.4 |
| | *28* | | 10.4 | 20.9 | 40.9 |
| Hearing Aid Noise Criteria, A weighted equivalent | *34* | | **7.4** | **17.9** | **37.9** |
| Quiet Environment Pink Noise | *35* | | 6.9 | 17.4 | 37.4 |
| Unacceptable Interference | *55* | | -3.1 | 7.4 | 27.4 |

§ Equation 3.

## COMPARISON WITH SUBJECTIVE MEASUREMENTS

### Subjective Measurements

*Persons with Impaired Hearing*

Table 12 summarises the immunity levels of Class[15] 1 and Class 2 hearing aid service from the discussion in Chapter 3, Table 8.

Table 12 Immunity Levels from Subjective Assessment of Hearing Impaired Persons

| *Perceptible* | *Immunity Level (ILM40 in dB re 1 V/m)* | |
|---|---|---|
| | *Class 1* | *Class 2* |
| no | 9 to 30 | > 30 |
| Yes | -3 to 8 | - |

*Persons with Normal Hearing*

A summary in Table 13 of *Immunity Levels* that could be appropriate for Class 1 and Class 2 hearing aid service is summarised from Table 10, Chapter 3 and compared with the hearing aid noise criteria from Table 11.

**Table 13 Immunity Levels from Subjective Assessment of Persons with Normal Hearing**

| *Perceptibility (from Table 10)* | *Immunity Level (ILM40 in dB re 1 V/m)* | |
|---|---|---|
| | *Class 1* | *Class 2* |
| not | ≥ 22 | ≥ 35 |
| just | - | 34 |
| moderate | 6 - 17 | 23 - 28 |
| annoying | < -3 § | ≤ 22 |
| c.f. Hearing aid noise criteria (from Table 11) | 17.9 | 37.9 |

§ Expected to be < 0.

The criterion using the hearing aid noise specifications is considered to be a reasonable compromise for specifying acceptable and possibly maximum levels of interference. It gives values consistent with the subjective assessments.

[15] Classes of use are first defined for this report at the beginning of Part B of Chapter 3.

## Using EHIMA Measurements [1]

The EHIMA report derives a criterion for interference to hearing aids using listening tests where a group of five listeners with normal hearing judged the "annoyance level" of simulated interference with a spectrum normalised[16] to hearing aid inputs in the presence of various background noises. The aim was to simulate what a person with normal hearing would hear. Figure 5 gives their result for responses in a "quiet environment" with pink noise equal to 35 dB SPL. Using 35 dB SPL as the response criterion and 10 volts per metre field strength, from Equation (3), the ILM40 is **17.4** dB re 1 volt per metre. This is almost the same as the hearing aid noise criteria.

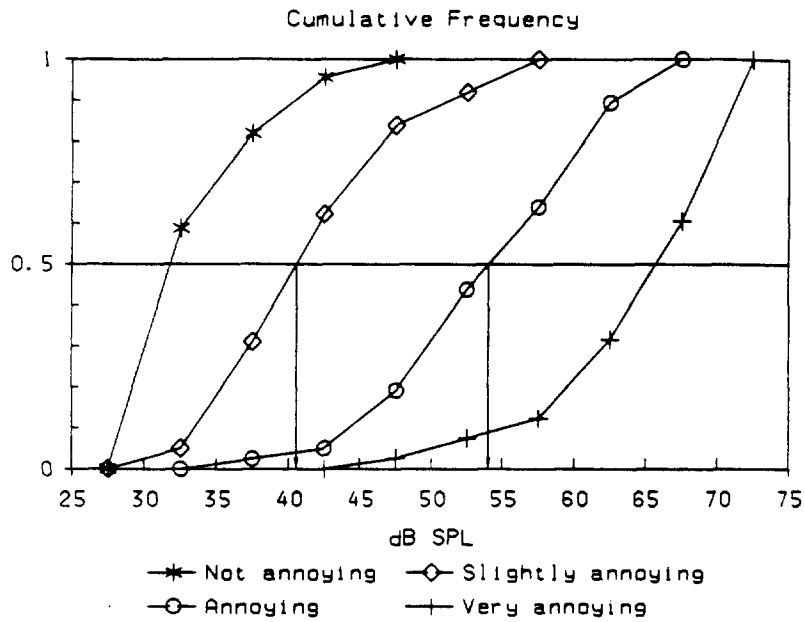


**Figure 5 EHIMA Annoyance Distribution for Five Listeners**

Source: Fig. 4.3.1 Cumulative distribution of responses in "quiet" environment (pink noise, 35 dB SPL), EHIMA GSM Project, "Development Phase", Project report (Revision A) [1], by permission.

### *Suitable Immunity Levels*

Figure 5 was considered in determining the criterion for the Australian Draft Standard on immunity discussed in Appendix 5. This standard is designed to ensure that not more than 10% of hearing aid users will be annoyed by interference from 2 watt digital cellular mobile stations (*digital mobile telephone*)

[16] The output spectra of the interference in a number of hearing aids were weighted by the inverse of the hearing aid acoustic gain and found to be approximately identical (as would be expected using the theory in Appendix 4). This spectrum represents the detected input referred interference. This approach supports the assertion that the output spectrum of any particular hearing aid is not relevant.