# Digital Signal Processing Hearing Aids, Personal FM Systems, and Interference: Is There a Problem?

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*Objectives:* To determine whether digital signal processing (DSP) hearing aids produce conducted radio frequency interference that can affect the use of personal FM systems, to quantify the nature of any such interference, and to discuss practical remedies.

*Design:* Sixteen DSP hearing aids were used. Measurements were made of the spectral characteristics of any conducted radio frequency interference produced by each aid with FM shoe and 40 cm direct audio input (DAI) lead when the DAI facility was enabled. Measurements were made with the aid, shoe, and lead inside an electrically screened chamber. The effect of DAI lead length was also investigated with one of the hearing aids. Finally, some subjective listening tests were carried out by using different FM systems coupled to a number of the aids.

*Results:* All but four of the DSP hearing aids tested produced readily measurable interference, with some much worse than others. Levels of interference were high enough with some hearing aids to be likely to significantly impede signal perception when the radio frequency of the interference coincided with the radio frequency of the FM system. This usually occurs intermittently as a result of the processor design of most DSP hearing aids. The listening tests suggested that when personal FM systems are in use with some DSP hearing aids, the interference would be audible, unpleasant, and detrimental to audio quality.

*Conclusions:* DSP hearing aids without low electromagnetic interference processors should not be fitted to clients if personal FM systems are expected to be used. Manufacturers of DSP aids should be encouraged to use low electromagnetic interference processors in their DSP hearing aid design. Meanwhile, FM systems should be used with DSP hearing aids in such a way as to ensure high received radio signal levels, and FM receivers should be switched off when not in use.

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Since the late 1990s, digital signal processing (DSP) hearing aids have increasingly replaced analogue hearing aids, since in principle they can be expected to offer more features and programming flexibility to meet the varied needs of users. In the United Kingdom, the change from analogue to DSP hearing aids for children has been monitored and evaluated as part of a government-funded project (MCHAS: Modernisation of Children's Hearing Aid Services, Bamford et al., 2004), resulting in new guidelines covering a range of activities associated with children's hearing aid services (see www. mchas m an .ac.uk).

Radio hearing aid systems, also known as FM (frequency-modulated) systems, are an important addition to the amplification options available to users. In such systems, an FM transmitter microphone is worn by the speaker, with the signal thereby transmitted using a specified radio frequency to an FM receiver worn by the hearing aid wearer. In most personal FM systems, the received signal is routed via the wearer's personal hearing aid(s) by way of a direct audio input (DAI) lead and a "shoe" that snaps onto the base of the hearing aid. In situations of unfavorable background noise (e.g., classrooms), where often the speaker is at a distance, the remote microphone FM systems provide significantly better signal-to-noise ratios (SNR) and therefore benefit for the listener than the hearing aid(s) alone (e.g., Crandell & Smaldino, 2000; Hawkins, 1984).

Most children with hearing aids in the United Kingdom would also use personal FM systems in certain environments (especially school). At an early stage of the MCHAS project, credible reports of significant interference when personal FM systems were used with certain DSP hearing aids were received. White noise was reported as being heard intermittently in some cases and constantly in others—particularly when the FM transmitter was switched off. The problem sounded similar to one that has been experienced by some cochlear implant users with FM systems (see e.g., Madell, 2004).

Personal FM systems are low-power, license exempt, one-way transmitter-receiver systems and are intended to be used over short ranges up to a few tens of meters to transmit a speaker's voice directly to the hearing aid of a hearing impaired user. The license exempt status means that the transmitters are only permitted to transmit at low power, typi-

Human Communication and Deafness Group (J.B., M.H.), University of Manchester, Manchester, United Kingdom; and Connevans, Ltd. (G.P.), Surrey, United Kingdom.

TABLE 1. DSP hearing aids used in the study

| |
|---|
| Philips Spaceline D71S 40 |
| GN ReSound Danalogic 283D |
| Oticon Spirit 700 |
| Oticon Digifocus |
| Oticon Spirit |
| A&M Select |
| A&M Selectra |
| A&M Triano-SP |
| Phonak Supero 412 |
| Phonak Supero 411 |
| Phonak Aero 211 |
| Phonak Aero 211AZ |
| Phonak Aero 311 |
| Starkey Gemini 13 AVMM |
| Widex Senso P37 |
| Widex Senso P38 |

*DSP = digital signal processing.*

cally 1 milliwatt or less. This means that to obtain good (i.e., noise-free) audio performance from a transmitter-receiver pair over useful distances, the receivers must have good radio sensitivity. Having a sensitive receiver to provide good audio performance necessarily means that the receiver is also sensitive to interference if it occurs in the same frequency band to which the personal FM system is tuned.

All digital processing systems, including DSP hearing aids, use a master clock to drive the internal processes. It is well known in the electronics and computer industry that the clock signals and their higher harmonics that are present in digital systems represent a potential source of interference to other systems. Since 1996, international laws have required manufacturers to control the interference produced by electronic systems. One of the most effective techniques for this in digital systems involves slowing the transition rates or edges of the clock signals inside the processor chips thus reducing the levels of high frequency harmonics enormously. Although this technique is widely used in industry, it is not routine in DSP hearing aids. This would not matter when the hearing aids aro being used alone, but used in conjunction with FM systems, DSP hearing aids could represent a potentially significant source of interference. Since the DAI lead connecting the personal FM receiver to the hearing aid is also the aerial for the receiver, any interference generated by a DSP hearing aid connected to the DAI lead would be expected to travel directly along the DAI lead into the personal FM system.. How the personal FM system then reacts to that interference, and to what extent the interference is audible to the listener, are therefore critical questions.

We set out to address these questions in this study. A number of current DSP hearing aids (see Table 1) were investigated by attaching them, via the appropriate FM shoes, to a DAI lead, which fed directly into a radio frequency spectrum analyzer. This allowed the extent of interference from the hearing aids to be examined visually and numerically. Additionally, subjective listening tests of some of the hearing aids when connected (again via the appropriate shoe and DAI lead) to a number of proprietary FM receivers were carried out with three normal-hearing listeners to assess the extent to which the radio frequency interference was a problem for the listener. Finally, the effect of altering the length of the DAI lead on the extent of interference was investigated.

## METHODS

Figure 1 illustrates the test setup used for the objective measurements of interference.

The hearing aid under test was attached with its shoe to a DAI lead of 40 cm in length. The DAI lead remained the same across all measurements; the shoes varied, because they are specific to particular hearing aids. The aid, shoe, and DAI lead were placed inside an electrically screened chamber as used for electromagnetic compatibility testing of electronic products. The use of a screened chamber was necessary to minimize the effect of external radio signals on the results. The chamber also contained radio frequency absorbing material to reduce internal reflections, very much like an acoustic anechoic chamber. The aid and DAI lead were placed on a nonconductive cardboard table suspended in the chamber, and the aid switched on to FM (direct audio input; the hearing aid microphone was live, but this had no effect on the measurements being made). The two electrical conductors in the DAI lead were connected together through a small capacitor at the interface connector in the side of the screened chamber. The capacitor ensured that all radio frequency energy produced by the aid was measured irrespective of which lead conductor it existed on, reflecting the way any interference would reach a connected FM receiver. The interface connector was grounded to the metal wall of the chamber and a standard radio frequency screened lead took the signal from the chamber to a radio frequency spectrum analyzer. The test system was effectively a closed box from which external influences were minimized. It may be considered as a radio frequency equivalent of a hearing aid test box, but far superior.

Measurements of each of the hearing aids were first undertaken with the shoe and DAI lead in place but with the aid switched off, to check the levels of inherent noise in the test system, including any external radio signals that leaked into the test

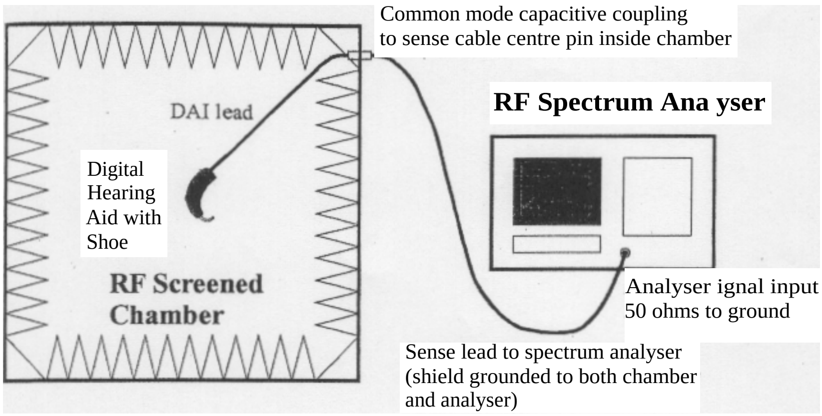


Fig. 1. Schematic of the test rig.

environment due to imperfect screening. The peak noise floor of the test system was at approximately 8 dBuV,* which was low enough to allow the interference to be detected from most of the aids tested. Since this study was carried out, it is has now been possible to reduce the noise floor further to extremely low levels of – 10 dBuV, allowing interference from all the aids to be detected.

The interference, if any, generated by each hearing aid and conducted by the DAI lead was recorded as a radio frequency spectrum in two stages. In both stages, the measurement bandwidth of the spectrum analyzer was fixed at 10 kHz because this approximates the audio bandwidth of personal FM systems. The first stage was to look for interference around a center 'frequency of 174 MHz, the frequency where personal FM systems are required to operate in the United Kingdom. These results are the most significant for the UK market and may be used to judge the relative performance and suitability of the hearing aids tested for use with FM systems in the United Kingdom. In other countries, where there are different national frequency allocations, center frequencies other than 174 MHz would be of interest. The second stage was to examine the amplitude of interference, if any, over a wide frequency range from 0.1 to 500 MHz to investigate the extent and position (in the frequency domain) of any peaks of interference. For all measurements, for any given model of DSP aid, we took the readings from a number of hearing aids (determined by how many we had at our disposal). Some FM shoes have an integral volume control; where this was the case, measurements were repeated for minimum, mid, and maximum positions of the control to see if this made any difference to the results.

Finally, we observed the effect of the length of the DAI lead on the spectrum of the radio frequency interference, since it would be expected that increased lead length would change the spectral distribution of the interference. This was done with one model of hearing aid only (A & M Selectra), using DAI lead lengths of 40, 50, 60, 70, 80, and 90 cm.

Three normal-hearing adults were used for the subjective listening assessments. The method used was to connect a hearing aid (now outside the chamber) to an FM receiver via the appropriate shoe and a 60-cm DAI lead, wrapping the DAI lead helically along a telescopic aerial connected to the input of the radio frequency spectrum analyzer (now disconnected from the screened chamber). This arrangement permitted the visual monitoring of both the approximate radio signal level received by the FM receiver from the FM transmitter and the instantaneous frequency of the interference produced by the DSP aid. The FM transmitter was worn by an assistant who used normal conversational voice levels into the transmitter microphone, moving to a distance that caused the received radio signal to be approximately 30 dBuV (a typical low value that might be encountered in normal classroom use as a teacher moves around the room). The sound field represented quiet office conditions. As the frequency of any conducted interference generated by the hearing aid moved and was tracked on the radio frequency analyzer screen, the receiving channel of the personal FM receiver was changed so that the frequencies coincided as often as possible. The subjective audibility of the interference was then monitored through a stetoclip attached to the hearing aid output. To establish that the interference occurred across a number of different aid/FM configurations, one of the subjects listened with each of three high-interference and one low-interference hearing aids (Widex P37, A & M Selectra; Philips Spaceline, Phonak Supero, respectively), coupled to each of the following proprietary FM systems: Connevans CRM220, Connevans fmGenie, Phonak Microvox, Phonic Ear 475, Phonic Ear Solaris, and Sennheiser

*dBuV is referenced to an electrical potential of 1 microvolt (AV), e.g., 0 dBuV = 1 AV, 10 dBuV = 3.16 AV, 20 dBuV = 10 AV, and 30 dBuV = 31.6 AV, etc.

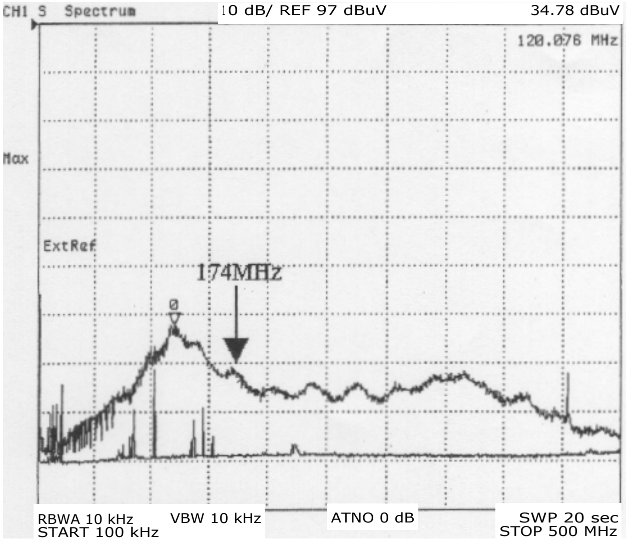


Fig. 2. Example of the wide-band peak noise spectrum for one of the digital signal processing hearing aids tested, illustrating the level and distribution of interference. The UK FM radio frequency (174 MHz) is indicated, as is the frequency and level of the maximum interference.

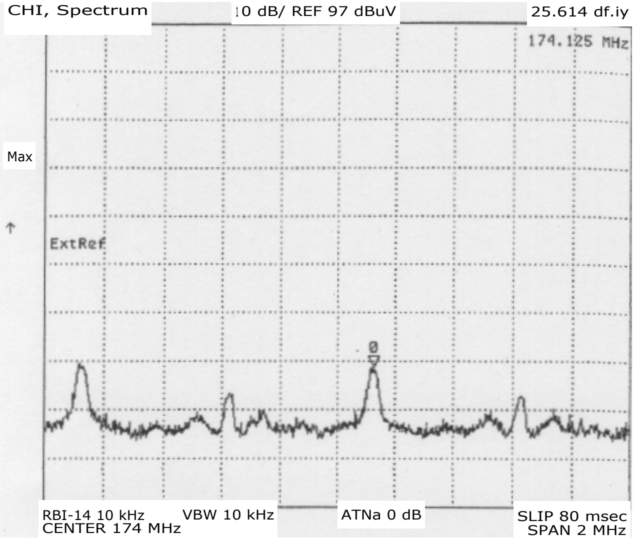


Fig. 3. Example of the narrowband peak noise spectrum centered at 174 MHz for one of the digital signal processing hearing aids tested (same aid as in Fig. 2); recording time, 5 sec.

Microport 2013PLL; the other two subjects selected one high-interference and one low-interference aid (Widex P37 and Phonak Supero, respectively) and listened to them when coupled to the Connevans fmGenie system, to confirm the subjective nature of the interference. The three listeners responded to two open-ended questions asking them (a) to describe the noise (if any) and (b) to comment on its acceptability.

Finally, since cordless FM receivers are becoming more common, one of the three adults listened for interference with a Phonak MLx FM receiver. This is an ear-level cordless radio receiver that is plugged into the FM shoe (it can also attach to other manufacturers' FM shoes, although not all hearing aids are MLx compatible due to the lack of appropriate shoes and modified battery doors), so that all that is required is to attach the shoe/receiver to the hearing aid. Since there is no DAI lead, it was only possible to listen for interference (rather than see it at the same time on the radio frequency spectrum analyzer); furthermore, as the MLx receivers are fixed frequency, with no opportunity to change the frequency, it was necessary to wait to see if the interference would drift across the required receiving frequency.

## RESULTS

The objective radio frequency interference tests showed most of the hearing aids generating high levels of interference. Figure 2 shows a typical wideband peak noise spectrum (width, 500 MHz) for one of the highest interference DSP aids. The lower trace is the noise floor of the measuring system. The spikes are commercial radio stations that leak into the test system. It can be seen that there is a peak of energy of approximately 35 dBuV amplitude at approximately 120 MHz (shown as 34.78 dBuV at 120.076 MHz by the test system marker function), a level that would be higher than the wanted radio signals into the FM receiver in some locations as a teacher moves around the classroom. Figure 3 shows the narrow (width, 2 MHz) peak noise spectrum for the same hearing aid with the spectrum centered at approximately 174 MHz (the frequency for personal FM systems in the United Kingdom). The trace was collected for 5 sec. Each of the two main peaks of energy is a band of radio frequency noise produced by the DSP aid and both are high harmonics (173rd and 174th) of the DSP processor clock: the peaks are separated by approximately 1 MHz—the clock frequency in the DSP processor. Note that the center peak of 25.6 pN is at 174.1 MHz, and the interference is likely, therefore, to be a problem for a listener using this DSP aid with an FM system in the United Kingdom.

When the recording for Figure 3 is taken and summed over a 3-minute period rather than a few seconds, it can be seen that the resultant spectrum (Fig. 4) shows rectangular blocks of interference centered at the same frequency points as the peaks in Figure 3. This is because each of the short-term peaks tracks across a frequency band either side of a center frequency, reflecting the tracking and pertur-

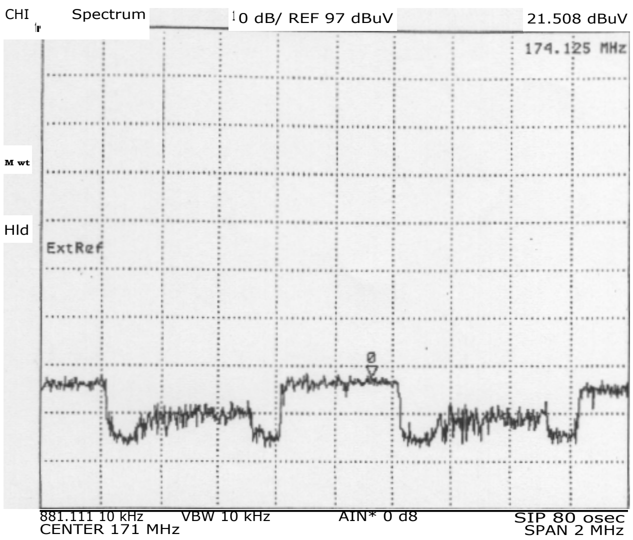


Fig. 4. Example of the narrowband peak noise spectrum centered at 174 MHz for one of the digital signal processing hearing aids tested (same aid as in Fig. 3); recording time was 3 min.

bations of the processor clock. Thus, one would expect the effect to come and go apparently at random for a listener with the FM system tuned to a particular frequency (as the peak crosses the receiving frequency band)—and this is in accord with the reports received from users. It was evident from visual inspection of the radio interference spectra that for all but one of the hearing aids the interference peaks were narrow bands of noise, tracking slowly across the frequency band; whereas for one aid (the Philips Spaceline), the interference was wider band, presumably because of processor design. The former are likely to cause intermittent interference, as they cross the FM receiver frequency, whereas the latter is likely to cause more continuous interference.

Table 2 shows the levels of conducted interference at or near 174 MHz from the DSP hearing aids tested. The table is ordered from those aids showing the most interference to those showing the least.

Where results from more than one DSP aid of the same model varied, the highest amplitude result (i.e., the worst case) has been entered in the tables. However, the variation in interference levels observed within groups of the same model aid was no more than 3 dB. As an aside, although this was not systematically investigated, the levels of interference wore unaffected (as expected) by the different gain, compression, and output settings that existed when measurements involved more than one hearing aid of the same model. In those FM shoes with an integral volume control, it was found that the volume position had no effect on the level of interference on the DAI cable.

TABLE 2. Peak levels of interference near 174 **MHz** in dBuV for all DSP aids tested and number of each model tested

| DSP hearing aid | No. of aids tested | Peak level of interference near 174 MHz In dBuV |
|---|---|---|
| Phonak Aero 311 | 1 | 29 |
| Widex Senso P37/38 | 6 | 26 |
| A&M Selectra | 3 | 25 |
| Philips Spaceline | 2 | 22 |
| Danalogic 283-D | 4 | 20 |
| Oticon Digifocus | 2 | 19 |
| A&M Select | 2 | 18 |
| Oticon Spirit | 4 | 15 |
| Starkey Gemini AVMM-13 | 1 | 12 |
| Oticon Spirit 700 | 2 | 12 |
| A&M Triano SP | 1 | 10 |
| Phonak Aero 211, 211AZ | 9 | <8 (not detectable above background noise) |
| Phonak Supero 411, 412 | 9 | <8 (not detectable above background noise) |

*DSP = digital signal processing.*

Table 3 shows the frequency and level of interference of the maximum peak taken from the wideband recordings for an example group of seven aids. It can be seen that the frequency of maximum interference (where measurable) occurs around 120 MHz in five aids, and 390 MHz in one other (although all aids with measurable interference showed peaks at both these frequencies). Antenna theory would suggest that the frequencies of these peaks are likely to be a function of the length of the DAI lead, with the 40-cm lead resulting in maximum interference amplitude at frequencies approximately 120 MHz and 390 MHz. For most of the aids tested, the largest peak is at approximately 120 MHz, where the interference amplitude is much greater than that at or around 174 MHz.

Table 4 shows how the frequencies of the two main maxima in the spectrum move as a function of DAI lead length. It is clear that users of personal FM systems in the United Kingdom are relatively fortunate in being able to use channel frequency allocations that do not coincide with the frequency regions of maximum interference. However, in countries such as the United States, where personal FM systems are operated at lower frequencies such as 79 MHz, the impact of the interference will be much more severe, especially with DAI lead lengths of 60 to 80 cm (which are more commonly used than 40-cm leads).

The subjective tests carried out with three listeners showed that when the FM receiver was tuned in such a way as to intercept as often as possible the varying frequencies of the interference peaks, the three high-interference hearing aids produced audible noise, and the low-interference aid produced no audible noise. The audible interference was vari-

TABLE 3. Frequency (MHz) and level (dBuV) of maximum interference, compared with level at or near 174 **MHz** for seven of the DSP hearing aids

| DSP hearing aid | Frequency of maximum interference, MHz | Level of maximum interference, dBuV | Peak level of interference near 174 MHz in dBuV |
|---|---|---|---|
| Starkey Gemini AVMM-13 | 121 | 21 | 12 |
| Oticon Spirit | 389 | 26 | 15 |
| Widex Senso P38 | 120 | 35 | 26 |
| Philips Spaceline D S40 | 122 | 32 | 22 |
| A&M Selectra | 123 | 33 | 25 |
| Phonak Aero 311 | 120 | 34 | 29 |
| Phonak Aero 211 | Not detectable | Not detectable | Not detectable |

*DSP = digital signal processing.*

ously described as white noise, steam, sea waves, crackling fireworks, and a harsh spitting sound. When asked to comment on the noise, all three listeners were very clear that it was highly undesirable: comments were that it "was an unacceptable racket," "totally crushes out the signal," "very distracting," "definitely unpleasant," and "was so unpleasant that it would put you off using FM." All three listeners noted that the unpredictability of the occurrence of the noise "one of the worst things," "wondering when it's going to happen again."

Importantly, the noise was obvious only when the received signal level was low (as in this case with a 30-dBuV received signal level), or, it was noticed, when the FM transmitter was switched off. When the transmitter was brought closer and the received signal level raised, the interference was not noticeable. The distance between the transmitter and receiver required to produce the 30-dBuV received signal level varied considerably between the various FM systems, with some needing a distance of 30 meters from the receiver and some only 8 meters. This indicates that some FM systems (those able to maintain strong radio signal levels over longer distances) have much better radio performance and should suffer less from the DSP interference in a typical classroom-sized environment.

With regard to the listening test with the MLx cordless receiver, the unpleasant acoustic nature of the interference, when it occurred, was the same. It was noted that the Philips Spaceline D71 S40 was a particularly undesirable partner for the MLx because the audible white noise was present and described as "very unpleasant" for most of the time.

## DISCUSSION

The objective test measurements confirmed that when most of the DSP hearing aids tested were connected to a DAI lead, significant amounts of conducted interference were produced; and the subjective listening tests done (with hearing aid coupled via the DAI lead to an FM receiver, and with a relatively low, but not unusual, level of transmitted FM signal) confirmed that this interference is likely to be audible and unpleasant. Table 4 shows that there are two main interference peaks in the frequency range up to 500 MHz, and both are dependent on the length of the DAI lead. For the 40-cm lead, comparing across all the tested hearing aids, these resonance peaks appear to be around 120 and 390 MHz. The measurements done with different length leads suggest that the frequencies of the resonances reduce approximately linearly with lead length to approximately 64 and 200 MHz for the 90-cm lead. This is roughly halving of resonant frequency for a doubling of DAI lead length and is in accordance with the predictions of antenna theory.

All except four of the DSP hearing aids produced significant interference when connected to a DAI

TABLE 4. Effects of length of direct audio input lead on the frequency (MHz) of the lower and higher bands of maximum interference and on the peak level of interference

| DAI lead length used (with A&M Selectra DSP aid) | Frequency of lower band of maximum interference, MHz | Frequency of upper band of maximum interference, MHz | Peak level of interference up to 500 MHz in dBuV |
|---|---|---|---|
| 40 cm | 123 | 380 | 33 |
| 50 cm | 110 | 323 | 32 |
| 60 cm | 91 | 262 | 31 |
| 70 cm | 80 | 244 | 33 |
| 80 cm | 66 | 210 | 33 |
| 90 cm | 64 | 198 | 33 |

*DAI = direct audio input; DSP = digital signal* processing.

lead. However, the levels and characteristics of the conducted interference varied. Of the DSP hearing aids tested, the Phonak Aero 211 and 211AZ and the Supero 411 and 412 produced no measurable conducted interference up to 500 MHz, whereas the Phonak Aero 311, Widex P38, and A & M Selectra produced the most. This applies both to the frequency range used by personal FM systems in the United Kingdom (173 to 175 MHz) as well as to the wider measurement bandwidth up to 500 MHz. Note that the problem of interference is one that is specific to models of DSP hearing aids rather than to manufacturers' ranges of aids.

A common characteristic of all the DSP hearing aids tested, with the exception of the Philips Spaceline D71 S40, was that the interference consisted of harmonics of the DSP clock used in the aid. This clock typically seemed to be running at around 1 MHz and was clearly a low quality resistor-capacitor clock because it was unstable, changing frequency slightly as a function of time, battery voltage, temperature, and power demand. A small change in clock frequency makes no difference to the efficiency of a DSP processor but makes large changes to the high harmonic frequencies. For example, a frequency change of 10 kHz is only 1% for a 1-MHz clock, but the 174th harmonic at around 174 MHz will move by 1.74 MHz. This means that the frequency of the interference moves around over the whole of the frequency band used by personal FM systems. This is the reason why it is so hard for a user to track down what is causing the apparently random interference. It occurs only when the frequency of the conducted interference is the same as the frequency to which the personal FM receiver is tuned. The Philips Spaceline D71 S40 has a different interference spectrum characteristic to the others; this may be because it uses a spread spectrum technique on the processor clock to reduce the peak level of interference at any particular frequency. However, this process spreads out the interference so that it affects more radio channels at any one time.

In general, the worst case for external interference to affect a personal FM receiver is when there is no deliberate transmission from the associated transmitter. The receiver is then "open" to any signal that comes along at the frequency that it is tuned to. To prevent the normal background electrical noise present in all electronic systems from annoying the user, a circuit known as a "squelch" is used. All personal FM systems use a squelch circuit to cut off the output when the audio signal becomes noisy (i.e., when the signal-to-noise ratio [SNR] falls below a certain value). The squelch circuit may be considered as a sound gate that is shut when the received signal is weak or noisy (such as at long range) and open when the received signal is clear.

As we have seen, the interference from DSP hearing aids is typically a band of noise occupying many times the receiving bandwidth of the receiver that slides around a centre frequency as a function of time. There will be many occasions when the noise is not at the same radio frequency as the receiver frequency but some occasions when the noise frequency coincides with the receiver frequency. Whether this is likely to cause a problem will depend on the strength of the wanted signal from the transmitter entering the receiver. When there is no transmission on the receiver channel (i.e., the transmitter is off but the receiver remains on), if the level and spectral characteristic of the conducted interference from the DSP hearing aid is such that it can open the squelch gate (i.e., it is regarded as "signal" by the receiver squelch circuit), then the receiver will pick up and reproduce the audio characteristics of the interference. When the transmitter is on and the receiver is in range, then the squelch gate would normally be open, allowing the transmitted signal to be heard. What happens in this situation depends on the absolute and relative levels of the wanted transmitted signal versus the conducted interference. When FM receivers are in receipt of strong radio signals, they are operating in a mode known as "fully quieting." This means that the SNR is as good as it can get, and interference will be suppressed. This is important because it means that even if no sound is transmitted, the presence of the strong radio signal should prevent interference from being heard. Below a particular received signal level (which is dependent on the individual receiver design), the SNR begins gradually to degrade, and the effects of external interference will start to become noticeable.

Take an example of a personal FM receiver that has a sensitivity specification of 0.5 ,utV (or –6 dBuV in alternative units) for 26-dB SNR and suppose that the squelch circuit closes below an SNR of 26 dB. The squelch gate would normally open at a received radio signal level above 0.5 p.V. Suppose that a wanted transmitted signal is received at a moderate level of 70 ţi,V (37 dBuV) and that a Widex P38 is the hearing aid connected by DAI lead to the FM system. The Widex will produce some in-band conducted interference of 26 dBuV when the frequencies of the conducted interference and of the receiver coincide (see Table 2). The wanted radio signal level is higher than the squelch level therefore the squelch gate is open. However, the interference is only 11 dB (= 37 – 26 dBuV) below the level of the wanted signal, and the user would be likely to hear the wanted audio plus the interference at a poorer SNR of +11 dB rather than the +40 dB or more that could otherwise be expected with a "quiet" aid (assuming that the hearing aid microphone is muted or that the background noise is suitably low).

In a typical classroom or home, it is not unusual for the received signal level to fall much lower than this in some places due to "nulls" caused by the cancellation of direct and reflected radio waves; on these occasions, or if the transmitter is turned off while the receiver remains on, the conducted interference (when it occurs) will dominate. It should be borne in mind that when analogue hearing aids are coupled to FM receivers, they are by definition free of DSP interference, and good SNRs of around 30 dB are achievable from the better personal FM systems at much lower received signal levels of a few microvolts (see Rowson & Bamford, 1995, for other issues in FM SNRs). This is not to imply that we should be returning to analogue hearing aids but rather that the DSP interference issue needs to be addressed by manufacturers and that parents, care givers, and users of FM systems with DSP aids should be aware of the problem and the aversive behavior it might engender.

The limited subjective tests carried out in this study need to be extended and to be done with hearing-impaired listeners. However, the findings are in accord with numerous anecdotal reports we have heard from users of FM systems with DSP hearing aids, some of whom have indicated severe levels of annoyance. Personal FM systems are now commonly used with young infants who are too young to comment, and because they are now routinely fitted with DSP hearing aids, this must be further cause for concern.

Because MLx systems do not incorporate a DAI lead, it might be thought that these offer a solution to the problem. However, the listening tests indicated similar interference problems, and it may even be that the actual interference level reaching an MLx style receiver is greater in practice because the two devices are connected directly together. Furthermore, MLx systems typically have very low radio sensitivity, which results in much poorer SNR performance even over short ranges than is possible with conventional body worn personal FM systems. What the user hears through an 1VILx style receiver has much more white noise added to it by the receiver than would occur with a good body-worn receiver. Immunity to interference outside the radio channel that an MLx style receiver is tuned to is also poorer than in a conventional body worn FM receiver because there is insufficient physical space for a good channel filter.

It is difficult to prevent the interference from the DSP hearing aid traveling down the DAI lead of the conventional systems because the interference travels along the lead in "common mode," i.e., the interference exists equally on all the conductors in the cable. The difficulty with filtering out common mode interference is that the filter circuit has to work against some electrical reference potential such as "ground," "earth," or a "large" electrically conductive area. None of these exists between a hearing aid and the attached personal FM system. Another problem is that there is a limit to the impedance that may be used for a filter in the DAI cable because a high value will adversely affect the audio frequency response. Finally, filters take up space, and large additional units would not be popular with users. Despite these difficulties, some filtering is possible. Initial designs suggest that interference attenuation on the DAI lead in the region of 6 to 12 dB should be possible in an aesthetically acceptable package. Further work is ongoing in this area.

The use of an inductive neckloop with the personal FM system in conjunction with the "T" or "M-T" setting on the hearing aid, rather than direct coupling with the DAI lead, would eliminate the problem. It is known that this method of wearing is already preferred by some users such as teenagers for cosmetic reasons. However, there are limitations on the audio quality attainable by this method that could outweigh any potential advantages in respect of radio interference.

Hearing aid manufacturers could eliminate this interference for all practical purposes by following established low EMI (electromagnetic interference) processor chip design procedures, but this appears not to be happening in all but a few DSP aids. Until the manufacturers do this for all DSP aids, the best way to minimize interference is to fit "low EMI noise" aids and avoid the use of "high EMI noise" aids when personal FM systems with DAI are to be used. Additionally, the effects of the interference may be minimized by keeping the personal FM transmitter on when the receiver is in use (and muting the transmitter microphone when transmitted sound is temporarily not needed) and switching off the receiver when it is not needed. The stronger the received radio signal, the more any interference will be suppressed. It may therefore be beneficial to operate the transmitter at a higher power level, where this is possible and legally permitted, and/or reduce the distance between transmitter and receiver, where possible.

## CONCLUSIONS

In response to the question, "is there a problem?" the short answer is "yes, in most cases"; a small number of DSP aids in the study showed low levels of interference. The problem is caused by the digital processor chip in the DSP hearing aid that produces radio frequency interference that is conducted along the DAI lead into the FM receiver. The interfering effects are made worse by the fact that the processor clock frequencies are not stable, resulting in unpredictable, random bursts of white noise from the attached personal FM receiver. The bursts of interference occur only if the radio frequency of the interference is the same as the radio frequency of the channel to which the personal FM system is tuned. The interference becomes audible when the signal level from the transmitter is low (when it is at a distance or switched off).

Audiologists should request conducted EMI information from manufacturers so that low EMI products can be fitted when personal FM use is likely. In the longer term, pressure on the designers of DSP hearing aids is required to encourage the manufacture of low EMI products.

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