REVIEW

Combined electro-acoustic stimulation: a beneficial union?

Talbot, K.N. & Hartley, D.E.H.

Department of Physiology, Anatomy and Genetics, University of Oxford, Oxford, UK

Accepted for publication 20 August 2008
Clin. Otolaryngol. 2008, **33**, 536–545

Background: The most pressing problem facing cochlear implant research is no longer making artificial hearing a reality. Instead, it is to develop devices that can more clearly reflect the capabilities of the human auditory system. Current cochlear implants rarely provide adequate pitch perception. As hearing loss commonly affects higher, more than lower frequencies, a possible solution is to preserve acoustic hearing at low frequencies by inserting a short electrode array and thus deliver combined electro-acoustic stimulation (EAS).
Objective of review: To determine whether individuals with severe-to-profound high-frequency hearing loss have realised this predicted benefit of combined EAS, over conventional cochlear implants, with respect to pitch.
Type of review: A systematic review of publications pertaining to the benefits of combined EAS over conventional cochlear implantation, with specific reference to pitch perception.
Search strategy: A systematic literature search was conducted across multiple databases and supplemented by searching the reference lists of relevant trials and identified reviews.
Results: The included studies suggest an overall benefit of combined EAS, over conventional cochlear implants, with respect to pitch. In addition, (i) 13% sustained a total loss of low-frequency hearing post-implantation of the short electrode array and, (ii) 24% had >20 dB hearing loss across all frequencies and/or total hearing loss.
Conclusions: For patients with severe-to-profound high-frequency hearing loss combined EAS appears to offer a significant, everyday, long-term benefit. However, further clinical trials with larger numbers of candidates are necessary to confirm this finding. The risks involved cannot be ignored, but there is potential for a variety of strategies to improve the safety margin.

The cochlear implant is undeniably the first prosthesis to successfully integrate with the sensory functions of the human brain. Having delivered an auditory percept, the key challenge of cochlear implant research is to more faithfully replicate the capabilities of the human auditory system. An important step is to address one of the greatest frustrations of cochlear implant users; their crude pitch perception and, consequently, their inability to fully appreciate music.[1] As over half of the world's population speak tonal languages that are particularly reliant on pitch, these technological deficiencies also degrade the perception of speech.

At present, the physiological mechanisms responsible for pitch perception are poorly simulated in the cochlear implant. The resolution of the place-code is severely limited, not only by the low number of available electrodes, at best only about 4–8 are functional at any one time, but also by their inability to stimulate discrete neural populations due to the electrical spread of excitation.[1] In turn, the resolution of the temporal code is an order of magnitude poorer.[2] Consequently cochlear implants are only able to produce a crude pure-tone pitch sensation, whereas extracting pitch from complex sounds may prove impossible.

One intriguing solution stems from the recent relaxation of candidacy criteria for cochlear implantation.[3] Undeniably this has enabled individuals with residual low-frequency hearing to benefit from a significant improvement in the key auditory task of speech perception.[1] However, it may come at a cost; as advancing the electrode array into the scala tympani can damage the basilar membrane, leading to the destruction of the residual acoustic hearing and, subsequently, any remaining pitch perception.[4]

The technique of combined electro-acoustic stimulation (EAS) aims to nullify this trade-off.[1] By only partially inserting the electrode array into the cochlea the technological advances target the high-frequency hearing but leave the residual low-frequency acoustic hearing unscathed (Fig. 1)[5] – inevitably the acoustic hearing of a

Correspondence: Katherine Talbot, Department of Physiology, Anatomy and Genetics, University of Oxford, Keble College, Oxford OX1 3PG, UK. Tel.: +44 1865 272500; fax: +44 1865 272469; e-mail: katherine.talbot@keble.ox.ac.uk

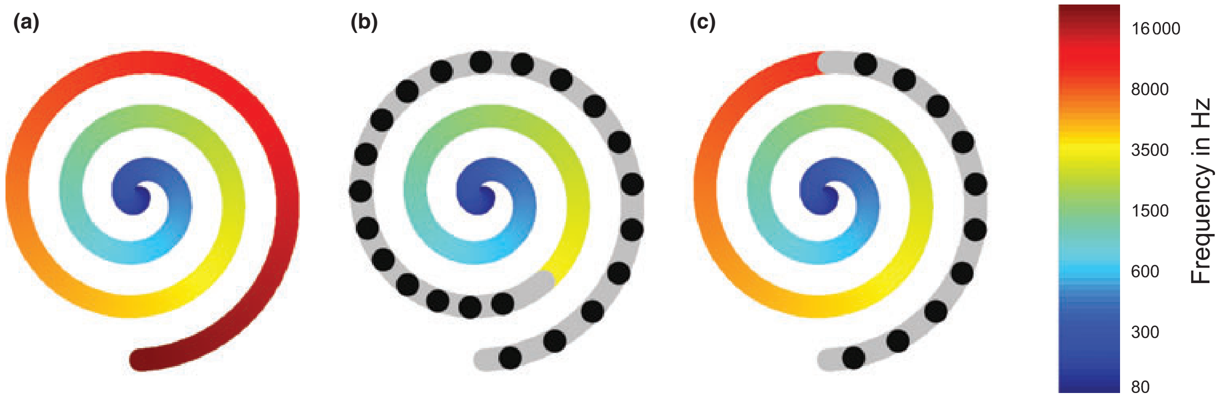

Fig. 1. Schematic of a cochlea with superimposed place-code (a). The depth of implantation with (b) conventional cochlear implant, and (c) short cochlear implant are indicated by the grey lines, with black dots representing the active electrodes in the array.

typical recipient will require amplification but this can easily be provided by the use of an existing or new conventional hearing aid. This combination of electrical and acoustic hearing thus improves the proportion of the cochlea available for place coding, as well as the robustness of the temporal code. With 50% of all individuals above the age of 65 affected by presbyacusis, a condition which differentially targets high-frequency hearing, such a strategy has the potential to dramatically enhance the quality of life of our ageing population.[6] The aim of this article is to determine whether individuals with severe-to-profound high-frequency hearing loss have realised these predicted benefits of combined EAS, over conventional cochlear implants, with respect to pitch perception.

Methods

Two sets of studies were considered from the available literature. The inclusion criteria for each set were as follows:

Set 1 The auditory performance of patients with combined EAS was compared against either, their own 'electrical stimulation alone' condition, or against patients with conventional cochlear implants. A statement as to whether the result was significant, or not, had to be present. Specifically the auditory performance of individuals had to be assessed using tests largely dependent on pitch perception, e.g. speech/sentence recognition in noise or melody recognition. Only trials with ipsilateral combined EAS, by means of plugging the contralateral ear, were considered.

Set 2 The number of patients with increased acoustic hearing loss across all frequencies was compared with the number of individuals with preserved low-frequency acoustic hearing, post-implantation of a short intracochlear array. Again, pre-implantation all patients had severe-to-profound high-frequency hearing loss and residual low-frequency acoustic hearing. A *total loss of acoustic hearing* was defined as (i) no response obtained at the maximal level of the audiometer or (ii) a total or complete loss of hearing implied within the body of the text. A *substantial increase in acoustic hearing loss* was defined as (i) increased hearing thresholds across all frequencies of >20 dB between pre- and post-operative measurements, and/or (ii) a total loss of acoustic hearing.

The following search strategy was used:

1 *Sources Searched*: Medline (Dialog and Pubmed), The Cochrane Library, Embase, Cinahl, PsycInfo and AMED.

2 *Dates of Search*: 1950 (or start date of searchable records) to 30th April 2008.

3 *Language restrictions*: None.

4 *Subject Search Strategy*: Medline NHS Dialog interface (adapted for other databases), excluding letters, comments, editorials and case reports:

1.	COCHLEAR NEAR (IMPLANT$ OR PROSTHES$)
2.	COCHLEAR-IMPLANTS#.DE. OR COCHLEAR-IMPLANTATION#.DE. OR PROSTHESIS DESIGN#.DE.
3.	AUDITORY NEAR (IMPLANT$ OR PROSTHES$)
4.	1 OR 2 OR 3
5.	COCHLEA$
6.	IS.DE.
7.	EQUIPMENT
8.	APPLIANCE$1
9.	DEVICE$1
10.	6 OR 7 OR 8 OR 9
11.	5 AND 10
12.	4 OR 11
AND	Electric-Stimulation#.DE. OR (electr$ stimulat$) OR Acoustic-Stimulation#.DE. OR (acoustic stimulat$) OR electroacoustic

Key
DE. = MeSH Subject Heading
# = Exploded Subject Heading
$ = Truncation

In order to maximise sensitivity the outcome of pitch perception was not included as a search term.

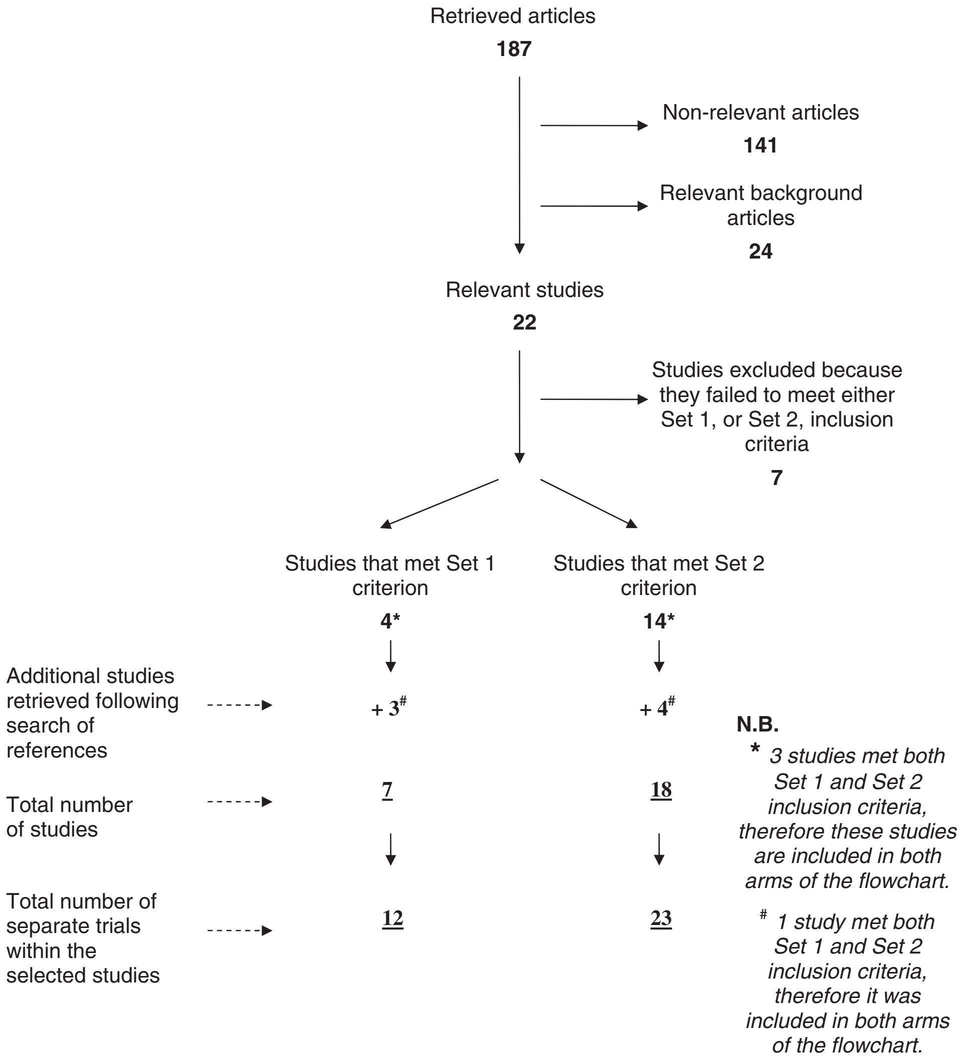

Fig. 2. Flowchart showing process by which relevant studies were selected from the articles retrieved by the search strategy.

Following removal of duplicates, a total of 187 potentially relevant citations were retrieved. To be included in this review the studies had to meet one set of inclusion criteria specified above, either Set 1, Set 2, or both Set 1 and 2. Additional citations were sought by searching the reference lists of relevant trials and reviews identified. [N.B. In some papers, there were several trials (with different variables and/or meeting different criteria), therefore these were analysed individually]. This breakdown is shown in the accompanying flow chart (Fig. 2).

The following data was then extracted from the selected studies:

1 *n*, the number of combined EAS patients involved in the trial,
2 insertion depth (mm) of the cochlear implant,
3 model/manufacturer of the short cochlear implant,
4 the form of hearing test used to assess post-operative auditory performance,

for Set 1,

1 performance in the post-operative hearing test; under (i) 'electrical stimulation alone' and (ii) 'combined EAS' conditions,
2 significance of the result, a result was recorded as significant if $P < 0.05$ or the word *significant* was clearly stated within the body of the text,

for Set 2,

1 number of patients post-implantation of a short cochlear implant with a (i) 'total loss of acoustic hearing', (ii) 'substantial increase in acoustic hearing loss' across all frequencies.

The quality of the selected studies, and where relevant, separate trials within individual studies, was assessed using a standard grading system (Table 1).

Table 1. Assessment of the level of evidence of the retrieved articles

Study	Type of study	Clearly defined control	Identified and appropriately controlled known confounders	Measured outcomes objectively	Sufficiently long and complete follow-up (n = not stated)	Level of evidence
Set 1						
Turner *et al.*,[7]	Cohort study	✔	✔	✔	✔	2b
	Cohort study	✔	✔	✔	✔	2b
Gantz *et al.*,[8]	Cohort study	✔	✔	✔	✔	2b
Kiefer *et al.*,[9]	Cohort study	×	✔	✔	✔	2b
Gantz *et al.*,[10]	Cohort study	✔	✔	✔	✔	2b
	Cohort study	✔	✔	✔	✔	2b
Lenarz *et al.*,[12]	Case report	–	–	–	–	4
	Case report	–	–	–	–	4
James *et al.*,[11]	Cohort study	×	✔	✔	✔	2b
Lorens *et al.*,[13]	Cohort study	✔	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b
Set 2						
Ilberg *et al.*,[5]	Case report	–	–	–	–	4
Skarzynski *et al.*,[31]	Cohort study	×	✔	✔	×	4
Gantz *et al.*,[32]	Cohort study	×	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b
Skarzynski *et al.*,[33]	Case report	–	–	–	–	4
Wilson *et al.*,[34]	Case report	–	–	–	–	4
Gantz *et al.*,[35]	Cohort study	×	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b
Gantz *et al.*,[36]	Cohort study	×	✔	✔	n	4
	Cohort study	×	✔	✔	n	4
Gstoettner *et al.*,[14]	Cohort study	×	✔	✔	✔	2b
Kiefer *et al.*,[37]	Cohort study	×	✔	✔	✔	2b
James *et al.*,[38]	Cohort study	×	✔	✔	×	4
Kiefer *et al.*,[9]	Cohort study	×	✔	✔	✔	2b
Gantz *et al.*,[10]	Cohort study	×	✔	✔	n	4
Gstoettner *et al.*,[39]	Cohort study	×	✔	✔	✔	2b
James *et al.*,[11]	Cohort study	×	✔	✔	✔	2b
Lenarz *et al.*,[12]	Cohort study	×	✔	✔	×	4
Luetje *et al.*,[40]	Cohort study	×	✔	✔	✔	2b
Skarzynski *et al.*,[41]	Cohort study	×	✔	✔	✔	2b
Berrettini *et al.*,[42]	Cohort study	×	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b
	Cohort study	×	✔	✔	✔	2b

This was carried out by the first author and used the standard grading system provided by the Centre for Evidence Based Medicine (CEBM), Oxford. http://www.cebm.net/index.aspx?o = 1025.

To determine whether a cohort study should be assigned either the level 2b or 4, four factors were assessed,

1 Whether there was a clearly defined control cohort,

2 Whether known and established (as opposed to possible) confounders, were identified and appropriately controlled,

3 Whether outcomes were measured objectively,

4 Whether follow-up was sufficiently long and complete, this was taken to be a complete follow up greater than or equal to 3 months.

If a cohort study achieved 3 or more of these factors it was assigned the level 2b, if not it was assigned the level 4.

An attempt was made to combine the studies quantitatively. This was possible for the second set of studies, but the diversity and heterogeneity of behavioural outcome measures made this impossible for the first set of studies. A structured review of the first set of studies was therefore undertaken.

Results

Overall 187 papers were retrieved. A total of seven papers (with 12 separate trials) formed the first set of studies. On qualitative assessment of the level of evidence 83% of these trials scored a level 2b, the remainder a level 4. By tabulating the data (Table 2), an overall analysis suggested that 92% of these showed a significant benefit in pitch perception of combined EAS over conventional cochlear implants for individuals with profound-to-severe high-frequency hearing loss.

In turn, 18 papers (with 23 separate trials) formed the second set of studies. On qualitative assessment of the level of evidence 61% of these trials scored a level 2b, the remainder a level 4. Analysis of these data revealed that of individuals implanted with a short cochlear implant 13% lost all their residual acoustic hearing and 24% had a substantial increase in acoustic hearing loss (Table 3).

Discussion

This review of the literature indicates that, with respect to pitch perception, combined EAS may be of greater benefit to individuals with severe-to-profound high-frequency hearing loss than conventional cochlear implants. Admittedly the advantage was not ubiquitous, but nevertheless it is an important finding. On the other hand there is a very real risk that during the procedure patients implanted with the shorter cochlear implant, requisite for combined EAS, may lose a substantial proportion, if not all, of their residual acoustic hearing. These results, along with their implications for cochlear implant research, will now be discussed.

Table 2. Benefit of combined electro-acoustic stimulation (EAS) in pitch perception compared to conventional cochlear implants and the 'electrical stimulation alone' condition

	Study	Insertion depth of short cochlear implant (mm)	Manufacturer/ make of short cochlear implant	No. of combined EAS patients tested	Post-operative hearing test	Time-period after implantation (months)	Significant benefit of combined EAS y = yes, n = no
Compared to conventional cochlear implants	Turner *et al.*,[7]	10	Nucleus Hybrid	3	Speech recognition in noise	12	n
	Gantz *et al.*,[10]	10	Nucleus Hybrid	14	Speech recognition in noise	12	y
	Lorens *et al.*,[13]	18–22	MedEl Combi 40+/40+M	11	Speech recognition in noise	12	y
	Turner *et al.*,[7]	10	Nucleus Hybrid	3	Speech recognition in multitalker babble	12	y
	Gantz *et al.*,[10]	10	Nucleus Hybrid	14	Speech recognition in multitalker babble	12	y
	Gantz *et al.*,[8]	10	Nucleus Hybrid	5	Melody recognition	12	y
Compared to 'electrical stimulation alone' condition	Lorens *et al.*,[13]	18–22	MedEl Combi 40+/40+M	11	Speech recognition test in noise	12	y
		18–22	MedEl Combi 40+/40+M	11	Speech recognition test in noise	12	y
	Kiefer *et al.*,[9]	19–24	MedEl Combi 40+/40+M	12	Sentence recognition test in noise	12	y
	Lenarz *et al.*,[12]	16	Nucleus Hybrid-L	1	Sentence recognition test a in noise	1	y
		16	Nucleus Hybrid-L	1	Sentence recognition test b in noise	1	y
	James *et al.*,[11]	17	Nucleus 24 contour advance	7	Sentence recognition in multitalker babble noise	6	y

Table 3. Number of patients with (i) a substantial increase in acoustic hearing loss, (ii) a total loss of acoustic hearing, following short-electrode implantation

Study	Number of patients implanted with a short cochlear implant	Insertion depth of short cochlear implant (mm) (*P* = not specified but known to be partial)	Manufacturer/ make of short cochlear implant	No. of patients with substantial increase in acoustic hearing loss post-implantation	No. of patients with total loss of acoustic hearing post-implantation (na = data not available)
Ilberg *et al.*,[5]	1	20	MedEl Combi 40+	0	0
Skarzynski *et al.*,[31]	26	26.4	MedEl Combi 40/40+	5	5
Gantz *et al.*,[32]	3	6	Nucleus CI-24 (modification of)	0	0
	3	10	Nucleus CI-24 (modification of)	0	0
Skarzynski *et al.*,[33]	1	20	MedEl Combi 40+	0	0
Wilson *et al.*,[34]	1	20	MedEl Combi 40+	0	0
Gantz *et al.*,[35]	3	6	Nucleus CI-24 (modification of)	0	0
	6	10	Nucleus CI-24 (modification of)	0	0
Gantz *et al.*,[36]	3	6	Nucleus CI-24 (modification of)	0	0
	8	10	Nucleus CI-24 (modification of)	0	0
Gstoettner *et al.*,[14]	21	16–24	MedEl Combi 40+/40+M	4	3
Kiefer *et al.*,[37]	14	19–24	MedEl Combi 40+/40+M	2	2
James *et al.*,[38]	12	17–19	Nucleus 24 contour advance	6	3
Kiefer *et al.*,[9]	13	19–24	MedEl Combi 40+/40+M	2	2
Gantz *et al.*,[10]	48	10	Nucleus Hybrid	8	2
Gstoettner *et al.*,[39]	23	18–24	MedEl Combi 40+/40+M	10	7
James *et al.*,[11]	10	17	Nucleus 24 contour advance	3	3
Lenarz *et al.*,[12]	4	16	Nucleus Hybrid-L	0	0
Luetje *et al.*,[40]	13	p	Nucleus Hybrid	5	2
Skarzynski *et al.*,[41]	10	p	MedEl Combi 40+	2	1
Berrettini *et al.*,[42]	8	25	Nucleus 24 M-K	6	na
	11	19	Nucleus 24 contour	6	na
	11	17–19	Nucleus 24 contour advance	2	na
Total no. of patients implanted with a short cochlear implant	253		Total no. of patients	61	30
			Percentage of patients (%)	24	13

Benefits of combined EAS?

First and foremost these studies have shown that the central auditory system is able to combine an acoustic stimulation of the residual hearing with ipsilateral electrical stimulation of the cochlear nerve.[7–13] This is an extremely important finding as although animal experiments had indicated that information transfer within the auditory system was not substantially impaired by such a combination[5] there remained the possibility that disturbing interferences would still arise. The fact that combined EAS was able to deliver a pitch percept, let alone one that was superior to that provided by a conventional cochlear implant, is a seminal result. In addition, combined EAS provided an equivalent, if not significantly better, performance with respect to speech perception in quiet compared to a conventional cochlear implant.[5,9,11–14] Thus, this superior pitch perception does not appear to result in a reciprocal trade-off with the perception of speech in quiet.

Secondly, the combination of acoustic and electrical stimulation was not simply additive; instead, for the perception of speech in noise, it was often strikingly synergistic.[9,14] In other words, the auditory performance with combined EAS was greater than the sum of auditory performance in the 'acoustic stimulation alone' condition plus the 'electrical stimulation alone' condition. The mechanism underlying this unexpected synergy requires further investigation. Notably, the 'electrical stimulation alone' condition, known to be almost entirely reliant on temporal coding, consistently scored higher than the 'acoustic stimulation alone' condition. Thus the mechanism underlying the synergistic performance of combined

EAS probably stems from an improvement in the robustness of the temporal code.

As yet no similar breakdown of performance has been undertaken for tests of music appreciation. Thus whether combined EAS is able to deliver a similarly synergistic result in this area is yet to be determined. As the place code dominates melody recognition,[15] and the contribution of the cochlear implant to this code is virtually nil,[1] it is unlikely that any improvement with combined EAS would be synergistic. Indeed, work with contralateral combined EAS (in which the electrical stimulation is contralateral to the acoustic stimulation) supports this hypothesis,[16] although the presence of bilateral cues prevents direct comparisons being drawn. Nevertheless, within combined EAS, this potentially creates a dichotomy between the mechanism responsible for the improved speech perception in noise and the mechanism responsible for the improved music appreciation.

Thirdly, these benefits of combined EAS allow the prediction of a further, more fundamental, benefit for a specific cohort of patients; namely tonal-language speakers. Critically, native Mandarin-speaking conventional cochlear implant patients, on average, can recognise only 57% of Mandarin-Chinese tones correctly.[17] Unlike the use of intonation in the vast majority of Indo-European languages, in languages such as Mandarin-Chinese tone is used to convey lexical meaning. Its importance for speech comprehension cannot be over-stated. The preservation of tonal information using combined EAS could, hypothetically at least, provide a considerable advantage over conventional cochlear implants. Yet, despite the potentially massive market for this technology, only simulated trials have so far been undertaken in this field.[18] Although these did demonstrate a significant benefit of combined EAS, over conventional cochlear implants, this finding remains to be demonstrated in a controlled clinical trial.

Overall, 11 out of the 12 small trials showed a significant benefit in the perception of speech in noise and the appreciation of music. However, if combined EAS is to be considered the gold-standard for patients with severe-to-profound high-frequency hearing loss, consistent benefits need to be shown in larger trials.

How can the consistency of these benefits be increased?

As outlined in the methods section the candidacy of patients for combined EAS was largely determined by pure tone audiometry. Although essential for determining the type, degree and configuration of hearing loss, it is well established that such tests reveal very little about central auditory function.[19] Factors known to have a substantial effect on both the inferior colliculus[20–24] and primary auditory cortex,[25–28] such as, (i) duration of deafness prior to implantation, (ii) severity and pathogenesis of hearing loss and (iii) auditory experience prior to implantation, were not accounted for within individual trials. Consequently, despite the similarity in their hearing thresholds, the functional capacity of the central auditory system had the potential to be significantly different across the cohort of combined EAS candidates. Future trials with larger n numbers should statistically analyse the significance of these factors. By adjusting the candidacy criteria according to the outcome of such trials it might be possible to improve the consistency with which combined EAS delivers a significant benefit over conventional cochlear implants.

Then again it is not simply within individual trials that potentially confounding factors arise. One notably contentious variable between the papers reviewed was the depth of insertion of the short cochlear implant; how short should short be? The difficulties associated with reaching a definitive consensus on this issue will now be considered.

For the benefit of combined stimulation to be maximal the acoustic and electrical stimulation should be contiguous. Ideally each patient should have the insertion depth of their electrode array calculated to minimise the unstimulated gap in the tonotopic array.[29] In practice the single greatest obstacle to achieving this goal is that the relationship between electrode insertion depth and place frequency is poorly understood. Patients are therefore implanted with either a shorter 6–10 mm electrode array or with an incomplete insertion, up to 16–24 mm, of the conventional electrode array. This difference in length consequently introduces a major disparity in the number of active frequency channels available for electrical stimulation, the importance of which is yet to be ascertained – obviously in the case of residual acoustic hearing loss a longer electrode array would, in consolation, provide more points of electrical stimulation within the cochlea. In the future, large trials should attempt to compare the relative merits of these two methods. Then again, an improved understanding of the relationship between electrode insertion depth and place frequency would be of even greater value as it would enable the contiguity of acoustic and electrical hearing to be optimised for individual patients.

Overall, addressing these variables may generate a considerable impact on performance consistency in combined EAS. However, as with the assessment of any emerging technology the potential benefits must be weighed up against the potential risks.

Risks associated with combined EAS?

Only if the residual acoustic hearing is preserved can the proposed benefits of combined EAS be achieved; atraumatic cochlear implantation is therefore essential. Temporal bone studies have shown that an insertion depth greater than 24 mm (beyond the first turn of the cochlea) is likely to significantly elevate the risk of trauma and thus the loss of residual acoustic hearing.[30] In the reviewed papers, however, a substantial increase in acoustic hearing loss occurred in 24% of patients, and in 13% there was a total loss of acoustic hearing, even though their electrode arrays were, with the exception of Skarzynski *et al.* (2002) equal to or shorter than 24 mm.[5,9,10–12,14,31–42] Admittedly changes in audiological thresholds may not be reflected in shifts in functional abilities,[41] e.g. aided speech perception, but, at present, they provide the only available standard metric that is comparable across the literature.

Essentially this risk exists because the surgical procedure for combined EAS originates from conventional cochlear implantation in which preservation of residual acoustic hearing was not a priority. Nevertheless surgical techniques have evolved to address known and suspected detrimental factors, including (i) the use of 'cochlear view' X-rays to reduce electrode misplacement,[43] (ii) flexible pre-curved arrays to minimise insertion trauma,[44] and (iii) trials with intra-cochlear drug delivery to stem neurosensory degeneration.[45] These improvements have made, and will no doubt continue to make, significant advances in the safety of this procedure. Finally, it should not be forgotten that, even if the residual acoustic hearing is lost, it still remains possible to use the inserted short electrode array, and potentially combine this with electrical and/or acoustic hearing in the contralateral ear.[40,46]

Finally, is there not a risk that the residual acoustic hearing of the patient may decline further? If so, would it not be wiser to wait and implant a conventional cochlear implant at a later date?

This line of argument against combined EAS, as a long-term solution, is refuted by the following points.

Firstly, to preserve central auditory function the spiral ganglion cells should be re-stimulated as early as possible following hearing loss.[47] Secondly, combined EAS does not eliminate subsequent implantation of a conventional cochlear implant; especially as in this proposed scenario preservation of the low-frequency acoustic hearing range would no-longer be an issue.[48,49] Of course, the option of further surgery would ultimately depend upon both the wishes of the individual and available funds. Thirdly, a recent study by Yao *et al.* (2006) has demonstrated that within the low-frequency range the threshold of hearing in adults that meet the candidacy criteria for combined EAS remains relatively stable; only dropping an average of 1.05 dB, per year. Thus within this cohort subsequent auditory decline may not even be an issue.[50] Consequently, withholding the use of combined EAS in anticipation of further auditory decline necessitating a conventional cochlear implant does not appear justifiable. A long-term trial is necessary to prove this theory.

Conclusion

In conclusion, for patients with severe-to-profound high-frequency hearing loss combined EAS may offer a significant, everyday, long-term benefit over conventional cochlear implants. Larger trials, allowing a greater range of factors to be analysed, are necessary to ensure the candidacy criteria are stringent enough to consistently deliver this advantage. Admittedly the risk of total acoustic hearing loss cannot be ignored, but developments in surgical technique will no doubt continue to improve the safety-margin. Ultimately by uniting the conserved sensory function of the individual with one of the most successful prostheses, combined EAS will facilitate the optimum treatment of each patient; namely their treatment as an individual.

Keypoints

- In comparison to the human auditory system current cochlear implants provide poor pitch perception.
- Combined EAS may provide a solution, as the conserved acoustic low-frequency hearing can supplement the electrical stimulation of the high-frequency hearing.
- A systematic review of the available literature showed that combined EAS may have a benefit over the traditional cochlear implant in pitch perception.
- Thirteen per cent of patients experienced a total loss of low-frequency acoustic hearing post-implantation of a short intra-cochlear array.
- Larger clinical trials are required, but this technology has the potential to significantly improve the pitch perception of individuals with conserved acoustic low-frequency hearing.

Conflict of interest

None to declare.

Acknowledgements

We thank Steve Sharp (Information Specialist, NLH Specialist Library for ENT and Audiology) for his advice with our search strategies. We are also grateful to Prof. G.M.

O'Donoghue, and 2 anonymous referees for their insightful comments on earlier versions of this manuscript. This work was supported by the Wellcome Trust.

References

1 Zeng F.G., Popper A.N. & Fay R.R. (2004) *Cochlear implants: auditory prostheses and electrical hearing*. Springer-Verlag, New York, NY
2 Zeng F.G. (2002) Temporal pitch in electric hearing. *Hear. Res.* **174,** 101–106
3 Cohen N.L. (2004) Cochlear implant candidacy and surgical considerations. *Audiol. Neurootol.* **9,** 197–202
4 Hodges A.V., Schloffman J. & Balkany T. (1997) Conservation of residual hearing with cochlear implantation. *Am. J. Otol.* **18,** 179–183
5 von Ilberg C., Kiefer J., Tillein J. *et al.* (1999) Electric-acoustic stimulation of the auditory system. New technology for severe hearing loss. *ORL J. Otorhinolaryngol. Relat. Spec.* **61,** 334–340
6 Blanchfield B.B., Feldman J.J., Dunbar J.L. *et al.* (2001) The severely to profoundly hearing-impaired population in the United States: prevalence estimates and demographics. *J. Am. Acad. Audiol.* **12,** 183–189
7 Turner C.W., Gantz B.J., Vidal C. *et al.* (2004) Speech recognition in noise for cochlear implant listeners: benefits of residual acoustic hearing. *J. Acoust. Soc. Am.* **115,** 1729–1735
8 Gantz B.J., Turner C., Gfeller K.E. *et al.* (2005) Preservation of hearing in cochlear implant surgery: advantages of combined electrical and acoustical speech processing. *Laryngoscope* **115,** 796–802
9 Kiefer J., Pok M., Adunka O. *et al.* (2005) Combined electric and acoustic stimulation of the auditory system: results of a clinical study. *Audiol. Neurootol.* **10,** 134–144
10 Gantz B.J., Turner C. & Gfeller K.E. (2006) Acoustic plus electric speech processing: preliminary results of a multicenter clinical trial of the Iowa/Nucleus Hybrid implant. *Audiol. Neurootol.* **11** (Suppl. 1)**,** 63–68
11 James C.J., Fraysse B., Deguine O. *et al.* (2006) Combined electroacoustic stimulation in conventional candidates for cochlear implantation. *Audiol. Neurootol.* **11** (Suppl. 1), 57–62
12 Lenarz T., Stover T., Buechner A. *et al.* (2006) Temporal bone results and hearing preservation with a new straight electrode. *Audiol. Neurootol.* **11** (Suppl. 1), 34–41
13 Lorens A., Polak M., Piotrowska A. *et al.* (2008) Outcomes of treatment of partial deafness with cochlear implantation: a DUET study. *Laryngoscope* **118,** 288–294
14 Gstoettner W., Kiefer J., Baumgartner W.D. *et al.* (2004) Hearing preservation in cochlear implantation for electric acoustic stimulation. *Acta Otolaryngol.* **124,** 348–352
15 Smith Z.M., Delgutte B. & Oxenham A.J. (2002) Chimaeric sounds reveal dichotomies in auditory perception. *Nature* **416,** 87–90
16 Kong Y.Y., Stickney G.S. & Zeng F.G. (2005) Speech and melody recognition in binaurally combined acoustic and electric hearing. *J. Acoust. Soc. Am.* **117,** 1351–1361
17 Wei C.G., Cao K. & Zeng F.G. (2004) Mandarin tone recognition in cochlear-implant subjects. *Hear. Res.* **197,** 87–95
18 Luo X. & Fu Q.J. (2006) Contribution of low-frequency acoustic information to Chinese speech recognition in cochlear implant simulations. *J. Acoust. Soc. Am.* **120,** 2260–2266
19 Mazelova J., Popelar J. & Syka J. (2003) Auditory function in presbycusis: peripheral vs. central changes. *Exp. Gerontol.* **38,** 87–94
20 Snyder R.L., Rebscher S.J., Leake P.A. *et al.* (1991) Chronic intracochlear electrical stimulation in the neonatally deafened cat. II. Temporal properties of neurons in the inferior colliculus. *Hear. Res.* **56,** 246–264
21 Leake P.A., Snyder R.L., Hradek G.T. *et al.* (1995) Consequences of chronic extracochlear electrical stimulation in neonatally deafened cats. *Hear. Res.* **82,** 65–80
22 Leake P.A., Snyder R.L., Rebscher S.J. *et al.* (2000) Plasticity in central representations in the inferior colliculus induced by chronic single- vs. two-channel electrical stimulation by a cochlear implant after neonatal deafness. *Hear. Res.* **147,** 221–241
23 Moore C.M., Vollmer M., Leake P.A. *et al.* (2002) The effects of chronic intracochlear electrical stimulation on inferior colliculus spatial representation in adult deafened cats. *Hear. Res.* **164,** 82–96
24 Snyder R.L., Rebscher S.J., Cao K.L. *et al.* (1990) Chronic intracochlear electrical stimulation in the neonatally deafened cat. I: expansion of central representation. *Hear. Res.* **50,** 7–33
25 Hartmann R., Shepherd R.K., Heid S. *et al.* (1997) Response of the primary auditory cortex to electrical stimulation of the auditory nerve in the congenitally deaf white cat. *Hear. Res.* **112,** 115–133
26 Klinke R., Kral A., Heid S. *et al.* (1999) Recruitment of the auditory cortex in congenitally deaf cats by long-term cochlear electrostimulation. *Science* **285,** 1729–1733
27 Raggio M.W. & Schreiner C.E. (1999) Neuronal responses in cat primary auditory cortex to electrical cochlear stimulation. III. Activation patterns in short- and long-term deafness. *J. Neurophysiol.* **82,** 3506–3526
28 Kral A., Hartmann R., Tillein J. *et al.* (2002) Hearing after congenital deafness: central auditory plasticity and sensory deprivation. *Cereb. Cortex* **12,** 797–807
29 Dorman M.F., Spahr A.J., Loizou P.C. *et al.* (2005) Acoustic simulations of combined electric and acoustic hearing (EAS). *Ear Hear.* **26,** 371–380
30 Gstoettner W., Franz P., Hamzavi J. *et al.* (1999) Intracochlear position of cochlear implant electrodes. *Acta Otolaryngol.* **119,** 229–233
31 Skarzynski H., Lorens A., D'Haese P. *et al.* (2002) Preservation of residual hearing in children and post-lingually deafened adults after cochlear implantation: an initial study. *ORL J. Otorhinolaryngol. Relat. Spec.* **64,** 247–253
32 Gantz B.J. & Turner C.W. (2003) Combining acoustic and electrical hearing. *Laryngoscope* **113,** 1726–1730
33 Skarzynski H., Lorens A. & Piotrowska A. (2003) A new method of partial deafness treatment. *Med. Sci. Monit.* **9,** CS26–CS30
34 Wilson B.S., Lawson D.T., Muller J.M. *et al.* (2003) Cochlear implants: some likely next steps. *Annu. Rev. Biomed. Eng.* **5,** 207–249
35 Gantz B.J. & Turner C. (2004) Combining acoustic and electrical speech processing: Iowa/Nucleus hybrid implant. *Acta Otolaryngol.* **124,** 344–347

36 Gantz B., Turner C. & Gfeller K. (2004) Expanding cochlear implant technology: combined electrical and acoustical speech processing. *Cochlear Implants Int.* **5,** 8–14
37 Kiefer J., Gstoettner W., Baumgartner W. *et al.* (2004) Conservation of low-frequency hearing in cochlear implantation. *Acta Otolaryngol.* **124,** 272–280
38 James C., Albegger K., Battmer R. *et al.* (2005) Preservation of residual hearing with cochlear implantation: how and why. *Acta Otolaryngol.* **125,** 481–491
39 Gstoettner W.K., Helbig S., Maier N. *et al.* (2006) Ipsilateral electric acoustic stimulation of the auditory system: results of long-term hearing preservation. *Audiol. Neurootol.* **11** (Suppl. 1)**,** 49–56
40 Luetje C.M., Thedinger B.S., Buckler L.R. *et al.* (2007) Hybrid cochlear implantation: clinical results and critical review in 13 cases. *Otol. Neurotol.* **28,** 473–478
41 Skarzynski H., Lorens A., Piotrowska A. *et al.* (2007) Preservation of low frequency hearing in partial deafness cochlear implantation (PDCI) using the round window surgical approach. *Acta Otolaryngol.* **127,** 41–48
42 Berrettini S., Forli F. & Passetti S. (2008) Preservation of residual hearing following cochlear implantation: comparison between three surgical techniques. *J. Laryngol. Otol.* **122,** 246–252
43 Marsh M.A., Xu J., Blamey P.J. *et al.* (1993) Radiologic evaluation of multichannel intracochlear implant insertion depth. *Am. J. Otol.* **14,** 386–391
44 Adunka O., Kiefer J., Unkelbach M.H. *et al.* (2004) Development and evaluation of an improved cochlear implant electrode design for electric acoustic stimulation. *Laryngoscope* **114,** 1237–1241
45 Hochmair I., Nopp P., Jolly C. *et al.* (2006) MED-EL Cochlear implants: state of the art and a glimpse into the future. *Trends. Amplif.* **10,** 201–219
46 Novak M.A., Black J.M. & Koch D.B. (2007) Standard cochlear implantation of adults with residual low-frequency hearing: implications for combined electro-acoustic stimulation. *Otol. Neurotol.* **28,** 609–614
47 Leake P.A., Hradek G.T. & Snyder R.L. (1999) Chronic electrical stimulation by a cochlear implant promotes survival of spiral ganglion neurons after neonatal deafness. *J. Comp. Neurol.* **412,** 543–562
48 Di Nardo W., Cantore I., Cianfrone F. *et al.* (2007) Residual hearing thresholds in cochlear implantation and reimplantation. *Audiol. Neurootol.* **12,** 165–169
49 Fitzgerald M.B., Sagi E., Jackson M. *et al.* (2008) Reimplantation of hybrid cochlear implant users with a full-length electrode after loss of residual hearing. *Otol. Neurotol.* **29,** 168–173
50 Yao W.N., Turner C.W. & Gantz B.J. (2006) Stability of low-frequency residual hearing in patients who are candidates for combined acoustic plus electric hearing. *J. Speech Lang. Hear. Res.* **49,** 1085–1090

