Aspects of Voice Measurement with Young Users of Cochlear Implants

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ABSTRACT

This brief study has two essential aims. First, it is directed toward the measurement of changes in voice control that may be consequent on the overnight deactivation of cochlear implants (CIs) by individual young children in a residential school for the deaf. Second, the work is based on the exploratory use of a set of voice analytic procedures that, although developed in the first instance for work on connected speech with hearing-impaired children, have subsequently been applied extensively in voice clinic environments. Acoustic and electrolaryngograph speech recordings have been made and analyzed for a group of children with CIs, early in the morning with acoustic and CI aids switched off and at the end of a normal day's use. Special attention has been paid to the analysis of perceptually relevant physical aspects of pitch, intonation, and voice quality. Differences in voice control between these conditions of implant use have been found for all of the children.

KEYWORDS: Voice, cochlear implant, children, pitch, loudness, quality, EGG, Lx, laryngograph

Learning Outcomes: As a result of this activity, the participant will be able to (1) define ways that voice in connected speech can be evaluated; (2) describe how the percepts of pitch, loudness, and voice quality link to vocal fold vibration; and (3) define "range" and "regularity," with special reference to hearing impairment.

The essential aim of most people with a disability is to enjoy the benefits of integration into ordinary society. The young cochlear implant (CI) user now often has the real possibility of achieving the abilities to speak and to hear the speech of others with a facility that was not previously attainable. Full integration is not yet feasible, however; for example, hearing and speaking effectively in the noisy environments inhabited by hearing peers are not always readily possible.

To gain more knowledge of the complex feedback system that exists when users of a CI respond to the speech of other people and also monitor their own speech production, several researchers have temporarily, and very briefly, broken the feedback loop by running tests with the implant switched off. Bharadwaja et al[1] studied foreign vowel production with CI aids switched off intersyllabically for 0.3 to 1.5 seconds, and in a parallel study[2] examined the effect of CI deprivation for 0.9 to 5 seconds on the production of native vowels. A prior and rather thorough study by Poissant et al[3] made use of five monosyllabic and three two-syllable words, elicited from pictures, placed at the end of a brief standard carrier phrase. Recordings were made sequentially, once with CI on and once with CI off. This use of auditory feedback interruption with CIs also has been employed as a tool by Higgins et al,[4] Tobey et al,[5] and several other researchers. An essential result of these investigations can be summarized by a quotation from Poissant et al[3]: "Once motor patterns are well established, [children] can maintain intelligible, accurate speech production even in the absence of auditory access to their own speech." Two factors, however, are common to all of these investigations. First, only a relatively brief CI switch-off interval was used in the protocol. Second, the lengths of speech samples elicited from the children were quite short (seconds).

The study of the use of CI aids in ordinary spoken language communication requires representative data collection that relates to tens of seconds, even minutes, of a child's speech. This then gives the basis for subjective evaluation and physical measurement to be directed at the ordinary levels of syntagmatic and discourse planning that are at the heart of normal conversation. For the purposes of control and comparison, standard read texts are widely employed in the voice clinic (e.g., "The Rainbow Passage"; "The North Wind and the Sun"; and "Arthur the Rat"). In initial preexploratory work with child CI users, we found, as reported above for shorter speech recordings, that even with the use of a long reading passage, there were often only minor differences between the spoken recordings made sequentially in the "with" and "without" aid conditions. Consequently, for the present exploration of the feedback influence of CIs, we have made recordings with the help of a group of child CI users in a residential school. This has made it possible to gather speech data immediately following an overnight CI switch-off and then to make another set of recordings at the end of a full day's use of the aids. (Please note that although all children made systematic use of their implants, three of the boys—B1, B2, and B3—also had contralateral acoustic aids. These were similarly out of action overnight. In the following discussion, *A* refers to a girl; *B* refers to a boy; and where two prostheses are at issue the term *aids* has been used.)

METHODS

Spoken language data were gathered from seven children with CIs (please see Table 1). Two types of speech material were elicited: sustained vowels and connected speech based on the child's reading of the story of "The North Wind and the Sun" after initial silent reading for familiarization. The rapid successions of different neural controls, which are essential for the production of sound sequences in ordinary connected speech, subject laryngeal phonatory mechanisms to ranges of activity that continually test their function to a depth that is quite unattainable by the sole use of sustained vowels. Consequently, the present brief discussion is based only on analyses of these complete, ~90-second recordings of connected speech. The children's chronological ages ranged from 11 years 11 months, to 14 years 4 months. This age range has made it possible, for some of the boys, to check an aspect of hearing in the control of the pubescent voice. Reading ages (based on the Access Reading Test[6]– standardized for use with normally hearing children) ranged from 6 years 2 months, to 13 years 9 months.

The children were recorded with their parents' consent and they participated willingly as volunteers. The recording sessions took place at ~6:30 A.M. before breakfast and in the evening at ~5:30 P.M. after a normal day's

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Bimodal Hearing and Bilateral Implantation; Guest Editor, Teresa Y.C. Ching, Ph.D.

Semin Hear 2011;32:42–52.
DOI: http://dx.doi.org/10.1055/s-0031-1271947.
ISSN 0734-0451.

Table 1 Chronological Ages; Reading and Speaking Abilities with and without Prosthese

Speaker (A, girl; B, boy)	Background					Pitch (Fx)			Clarity (Qx)		
	Age at Test (y; mo)	Reading Age (y; mo)	Speech Rating[15]	Aid(S)		Mean Fx Hz	SD-oct	Roughness IFx %	Mean Qx %	80% Range Qx %	Roughness IQx %
A1	13;2	10;7	4	Without	CI Freedom	222.52	0.257	3.47	35.83	31.1, 43.2	36.36
			5	With		225.72	0.277	6.81	39.78	35.8, 47.7	47.29
A2	13;6	6;2	2	Without	CI Freedom	252.32	0.191	5.93	44.40	37.9, 54.8	46.27
			3	With		246.77	0.270	10.64	46.04	38.1, 56.6	59.86
A3	14;1	6;10	2	Without	CI Cochlear Espirit 3G	219.76	0.434	26.53	46.01	36.8, 56.8	57.91
			2	With		226.60	0.346	8.81	49.64	40.4, 60.1	51.82
Bb	NA			Normal		207.92	0.276	7.09	47.08	39.1, 57.1	28.07
B1	12;1	9;11	4	Without	Advanced Bionics Harmony C1 and Naida	156.60	0.482	15.72	40.50	34.8, 48.1	37.56
			5	With		166.3	0.53	12.35	44.35	37.8, 54.8	37.89
B2	11;11	6;5	3	Without	CI Freedom and Naida	107.25	0.669	39.14	47.43	38.7, 56.5	44.88
			5	With		137.62	0.511	22.74	41.85	36.9, 50.3	52.34
B3	14;4	12;9	3	Without	CI Freedom and Power Max	236.14	0.37	13.62	35.53	30.6, 46.8	47.92
			4	With		268.06	0.264	12.15	28.13	22.7, 37.8	53.32
B4	12;10	13;9	3	Without	CI Cochlear Espirit 3G	175.77	0.604	29.54	32.94	24.5, 44.0	51.61
			5	With		203.29	0.422	9.09	43.03	36.9, 52.7	42.97

CI, cochlear implant; FX, cycle by cycle vocal fold frequency; SD-oct, standard deviation in octaves; IFx %, percentage irregularity of vocal fold frequency; Qx %, percentage vocal fold contact phase; IQx %, percentage irregularity of the vocal fold contact phase.

use of the aids (please see Table 1 for details of the CI and acoustic aids used). Quiet, furnished rooms with low reverberation time were used for all recordings.

The recording equipment was provided by Laryngograph Ltd (Sutton, United Kingdom). A standard Knowles (Itasca, IL) pressure sensitive nondirectional microphone was used for the acoustic signals, placed at ~6 inches below the mouth. Standard large Laryngograph® electrodes were used to obtain synchronous electroglottograph signals.[7] Data were collected with a standard Laryngograph microprocessor with its USB laptop connection. Digitization was at 16 kHz, 16 linear bits for each channel. The subsequent analyses were all made with the same Laryngograph hardware and software package that was used for recording. The analyses were based on earlier work[8,9] but now using psychophysically motivated binning,[10] in which the sizes of the analysis bins are derived from pitch difference limens for connected speech.

Data Acquisition

In Fig. 1, the sound sequence [tr{v][11] ("trav") has been cut from the phrase "the traveler took his coat off" in the complete recording of the North Wind and the Sun, used in this study for all the children. This sequence is of interest in illustrating the methods of data analysis because it has both voiced and voiceless sounds in succession and ends with a voiced fricative. It has been spoken here by child A3 early in the morning before breakfast and before she made use of her CI. This example shows considerable diplophonia, and it is of special interest to examine how such an irregular vocal fold vibration can be quantified. Fig. 1A is based on a cycle-by-cycle analysis of vocal fold frequency and peak acoustic pressure. These

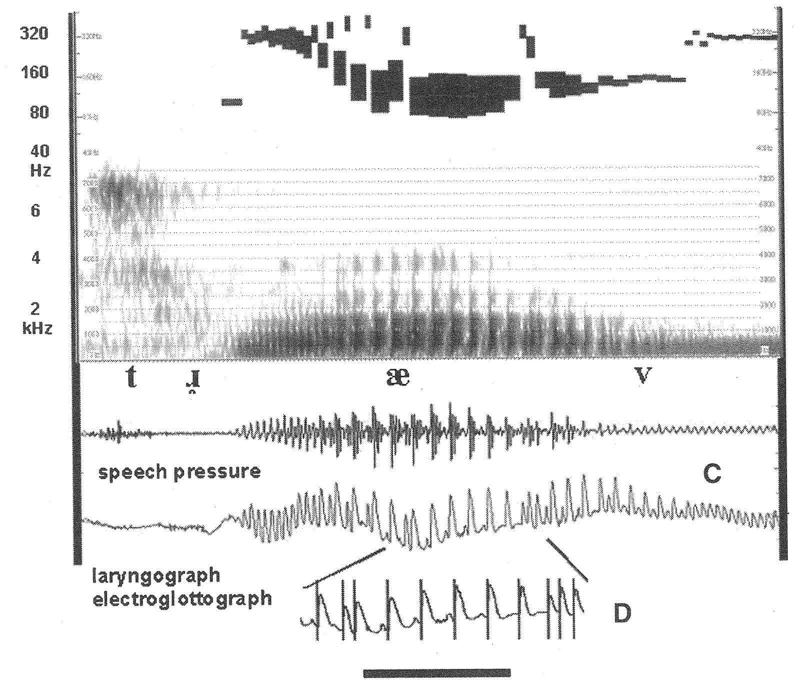

Figure 1 A3 without cochlear implant (CI) aid reading [т≤⇓ѣ]. (A) A real-time representation of intonation: note diplophonic two pitched breaks at the onset of the vowel in the center of the figure. (B) Broadband spectrogram: note the poor formant definition. (C) Speech pressure and laryngograph waveforms that have been used to derive the "pitch and loudness" components of Fig. 1A: note their timing irregularity. (D) Expansion of part of Fig. 1C to show how the closure epoch markers used for instantaneous frequency measurement have been obtained and to explain how the diplophonia in Fig. 1A has been measured and displayed.

two measurements are, respectively, physical correlates of perceived pitch and loudness, and they have been combined in this figure to give an indication of the speaker's control of her intonation, with the vertical width corresponding to loudness and the height of the trace to pitch. This information also is designed for real-time use in interactive voice therapy and for complementary employment as the basis for detailed voice analysis.

Fig. 1C shows the acoustic pressure and electrolaryngograph (glottograph) waveforms from which Fig. 1A is derived. Fig. 1D gives more detail on the excitation epoch markers that are used to define each cycle and that make it possible to get accurate real-time "pitch" analyses based on instantaneous frequency measurements. They are automatically produced by the analysis and display software and hardware.[12] The special advantage of this approach for real-time biofeedback therapy[7,8,10,13] is that it clearly shows pitch-related irregularities by breaks in the contour and changes in loudness-related amplitude by variations in the contour width. In principle, this information also is shown in the classic wide-band spectrogram of Fig. 1B by the spacing between its vertical striations. For work on voice pitch, however, Fig. 1A has the advantages of simplicity and immediate relevance. This type of display, and the analysis on which it is based, can lead to far more probing evaluation than is feasible from the use only of the acoustic microphone signal.

Fig. 2 examines the same utterance using the same analysis and display technique to show an aspect of the effect on A3's voice production of her use of her CI during a school day following the recording made for Fig. 1 the same morning. The reduction in diplophonia shown in Fig. 1A for the vowel [{] and the use of a more appropriate frequency are quite striking. It is evident that the use of her aid has enabled A3 substantially to overcome the challenges posed by the [tr{] voiceless to voiced transition and to produce a far better [{v] sequence. Figs. 1C and 1D now show more normal vocal fold vibration with much better

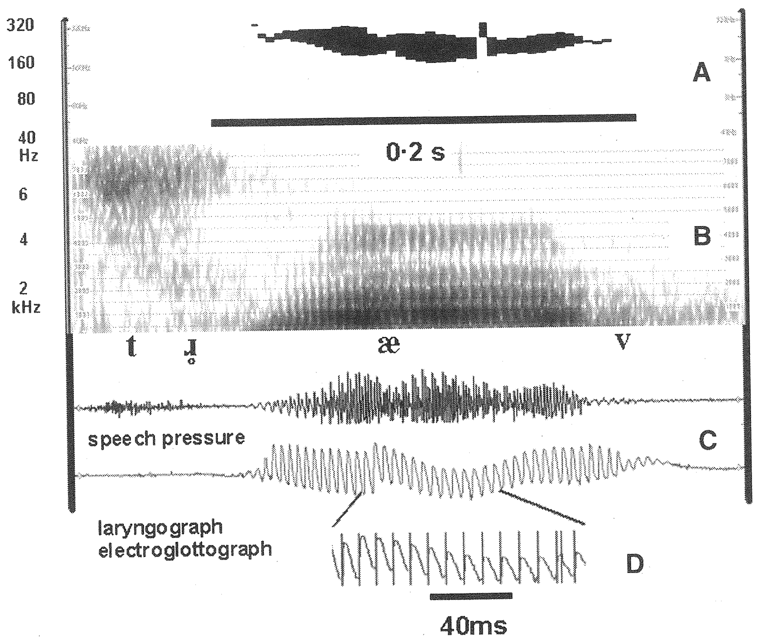

Figure 2 A3 with cochlear implant (CI) aid reading [τ≤⇓ɸ]. (A) Real-time representation of intonation: note the appropriate pitch, now without diplophonia. (B) Broadband spectrogram: note the better formant definition. (C) Speech pressure and laryngograph waveforms that have been used to derive the "pitch and loudness" components of Fig. 1A: note their timing regularity. (D) An expansion of part of Fig. 1C to show how the closure epoch markers used for instantaneous frequency measurement have been obtained and to indicate the vocal fold vibratory nature of the improvement in pitch regularity.

definition of the vowel formants in the broad band spectrogram.

Analysis Methods

The possibility provided by Figs. 1 and 2 of a detailed examination of brief samples of connected speech data is of very great value in interactive voice therapy and also for research into particular aspects of production. It is also necessary, however, to summarize salient voice characteristics from larger more representative samples of connected speech that can be related to everyday communicative experience.

Fig. 3 gives an overview of some of the results of applying these techniques to the whole 90-second recording of a complete text. The main part of Fig. 3A shows the way in which the speaker's voice pitch range (based on vocal fold contact epoch frequencies [Fx]) is distributed. The higher on the graph, the more that part of the voice frequency range has been used. The marked diplophonic character of A3's voice when her aid is switched off is shown by the two main peaks in this elapsed time voice pitch distribution (eDFx1).[10] Her use of her implant has had a marked perceptible effect on her control of voice pitch and this is confirmed by the presence of a single main peak in Fig. 3B. There is also a very perceptible reduction in the pitch irregularities (creak) in her voice, and this is indicated by the difference between the pitch roughness distribution (CFx) inset plots in Figs. 1A and 1B. CFx is based on the comparison of the Fx values of successive vocal fold cycles.[10,14] For a normal voice, this comparison leads to a simple, well-defined, diagonal plot of the data. When the voice has cycle-to-cycle pitch irregularities, these lead to more diffuse, broken, diagonal patterns. The CFx inset in Fig. 3A is more deviant from a well-defined diagonal than that

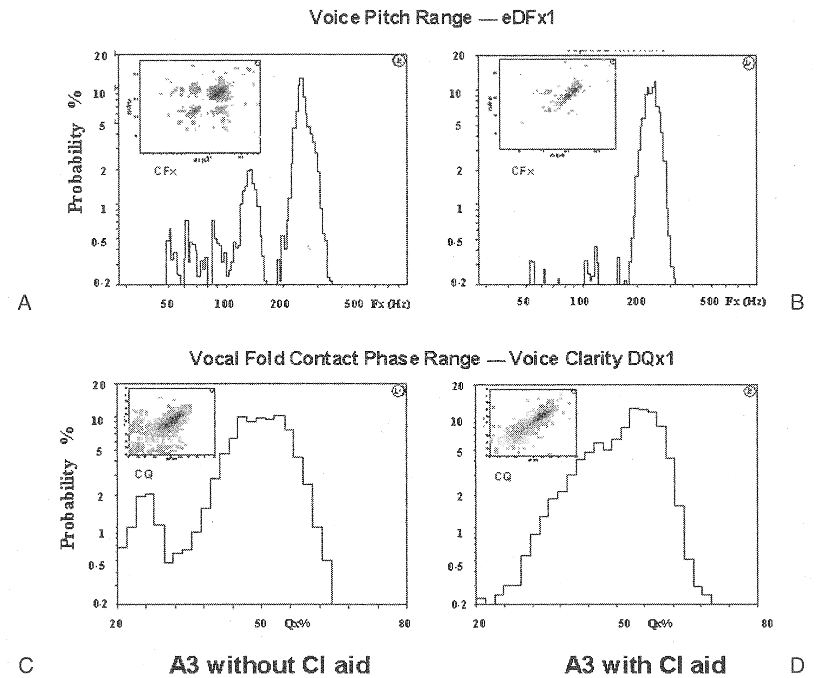

Figure 3 A3 running speech analyses. (A, B) These histograms show the way that the speaker has used her voice pitch for the whole of the read passage. She is diplophonic when she cannot hear herself so her pitch jumps over several octaves but this changes for the better when she uses her CI (B). The small insets, CFx, indicate pitch regularity. (C, D) These histograms tell us something about the way that her voice quality is controlled in terms of its contact phase in each cycle; (C) her voice quality tends to be breathy and rough: see the peak on the left for the breathiness and see the inset, CQx, graph for the irregularity. CI, cochlear implant; eDFx1, elapsed time voice pitch distribution; CFx, pitch roughness distribution; DQx1, closed phase distribution; CQ, close phase scatter plot.

of Fig. 3B and this is linked to readily perceptible voice pitch differences between the two recordings. The degree of departure from an ideal central diagonal can be used as an objective measure of pitch irregularity—IFx.[10] For these two analyses, IFx is respectively 26% (an abnormal degree of irregularity) and 9% (which is in the normal range of ~3 to 12%). Although her overall voice quality is still not good, the use of her implant has enabled her to achieve a voice pitch control that is comparable, in these terms, with that of her hearing peers.

Figs. 3C and 3D show an aspect of voice quality that depends on the speaker's control of vocal fold contact duration proportion (ratio of contact time to duration of vocal fold cycle [Qx %]). A breathy voice quality, for example, tends to be linked to a small contact duration in each cycle, as in the center part of Figs. 1C and 1D where the contact phase ratio is ~25%. Fig. 3C shows the distribution of her contact phase ratio (Qx %) during her reading of the whole text first thing in the morning with her CI turned off. The graph shows a small peak at ~30% Qx, in the breathy region of voice production, and a larger main peak at ~50% Qx. Fig. 3D shows a tendency with the use of the aid to higher values. With the CI turned on, at the end of a normal day's use, A3s's voice was less breathy. There is, however, another aspect of contact phase control that is of importance to perceived voice quality.[14] The regularity of Qx from vocal fold cycle to cycle contributes to an aspect of the perception of good voice quality. CQx is based on the comparison of successive values of Qx. A CQx plot whose diagonal is well defined indicates a good control of Qx. It is evident from the CQx insets of Figs. 3C and 3D that, once more, the use of her aid has helped A3 to improve another aspect of her voice control. It is, however, worth noting that the irregularity of Qx (IQx) is considerably greater at 52% even with the CI than would be expected for a normally hearing child (at ~30%), and this is an aspect that appears likely to be of importance both in regard to the design of CIs and also in respect of individual interactive voice therapy. A3's speech rating, based on a global subjective assessment[15] (please see the Table 1 and Discussion section), and these detailed observations may serve as guides in future therapy.

Figs. 4A and 4B for B1 also show the beneficial influence of a working day's use of hearing aids, although in this case both a CI and an acoustic aid were in bilateral use. Once more pitch irregularity, as shown by the inset CFx plots, has been reduced. There is also a marked improvement in the average contact phase quotient, Qx. This is accompanied by improvements in CQx where the use of the aids is linked to a greater regularity of contact phase over a greater range of Qx than for the "without aids" condition. The associated IQx contact phase irregularities for the "with" condition are still, however, greater than normal (see Bb in the Table 1).

Voice Analysis Summaries

Table 1 gives an overview for all the speakers, in both unaided and aided conditions, of the average values for the analyses of the whole ~90-second recorded texts. The graphs of Figs. 3 and 4, however, provide a much more useful indication of the effects of the overnight switch-off and of the individual child's voice strengths and weaknesses than it is possible to obtain from average values. A3, for example, is shown to have achieved a remarkable improvement in the reduction of her mean pitch irregularity in Table 1 when using her aid, but the inset of Fig. 3A shows that there is, nevertheless, high irregularity in the upper part of her pitch range. Similarly, her mean contact phase (Qx%) has only increased slightly in the "with" condition but Figs. 3C and 3D show that in the "without" condition, there is a large "breathy" voice component with low values of Qx% in the DQx% distribution. Similarly for the voice of B1, although the mean values of Fx and Qx are improved in the aided condition, the graphs show that there still remain problems to resolve in respect of his lower-frequency irregularity and breathiness. There is potential advantage in giving compact description of voice use via the graphical representations so as to help focus on particular voice difficulties.

Figs. 5 and 6 provide thumbnail summaries of the connected speech analyses for all of the children in this study, and in Fig. 5 there is a summary for a normally hearing boy (9 years 6 months of age). It has not been feasible to include CQx (contact phase cycle to cycle irregularity) plots in all these brief sets of analyses. A thumbnail CQx has, however, been inserted for the normally hearing boy Bb. Typically for normal voice control, his CQx plot is narrow with roughly half the irregularity found for the other voices in this study (please see the CQx insets in Figs. 3 and 4 and the values of IQx in Table 1). An addition to the summaries of Figs. 3 and 4 comes from the inclusion of long-term average spectra (LTAS) of each complete recording. These spectra show marked differences between the higher-frequency acoustic energy levels for A1 and A3 in comparison to A2, B1, B2, and B3. For B3, however, although his LTAS plots are similar, there are profound changes in his voice quality between the unaided and aided conditions. B3's voice is breaking, and in the unaided condition, his vocal fold physiology appears to determine the essentially bimodal shape of his frequency distribution (eDFx1) and gives a ragged diplophonic character to his pitch roughness distribution (CFx). In the aided condition, however, he has considerable success in maintaining his familiar treble voice with auditory feedback now, at least for the time being, exerting the major control. B4 presents with a very similar puberphonic example of the profound influence that can come from effective CI-aided auditory monitoring of voice pitch control.

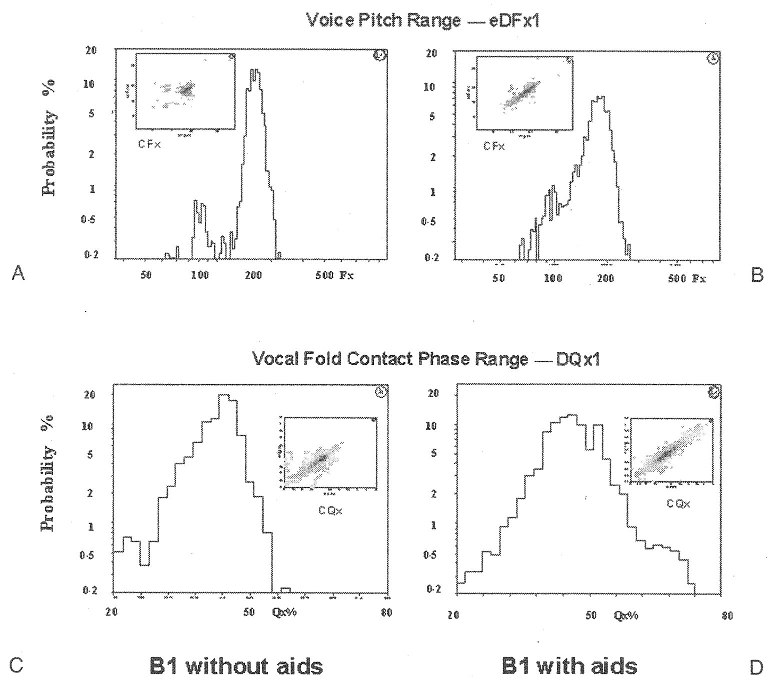

Figure 4 B1 running speech analyses. (A, B) This speaker does not have marked diplophonia but his speech is rather hoarse; when he can use his hearing to control his voice pitch, he has less hoarseness, which is shown by the smoother diagonal in the inset. (C, D) These histograms of contact phase show that with the use of his aid, this speaker has made a big improvement in this aspect of his voice quality, not only in the increased mean contact but also in contact regularity, as shown by the inset cross-plot graphs, CQx. Although in this respect he is the best of the whole group, a normal voice has much less irregularity (IQx in Table 1). eDFx1, elapsed time voice pitch distribution; CFx, pitch roughness distribution; DQx1, closed phase distribution; CQX, closed phase scatter-plot.

DISCUSSION

The essential aim of this brief, exploratory, and rather informal study was to examine the influence that the use of CIs might have on the auditory control of voice production. As discussed above, prior work that was based on the comparison of brief recordings made with short

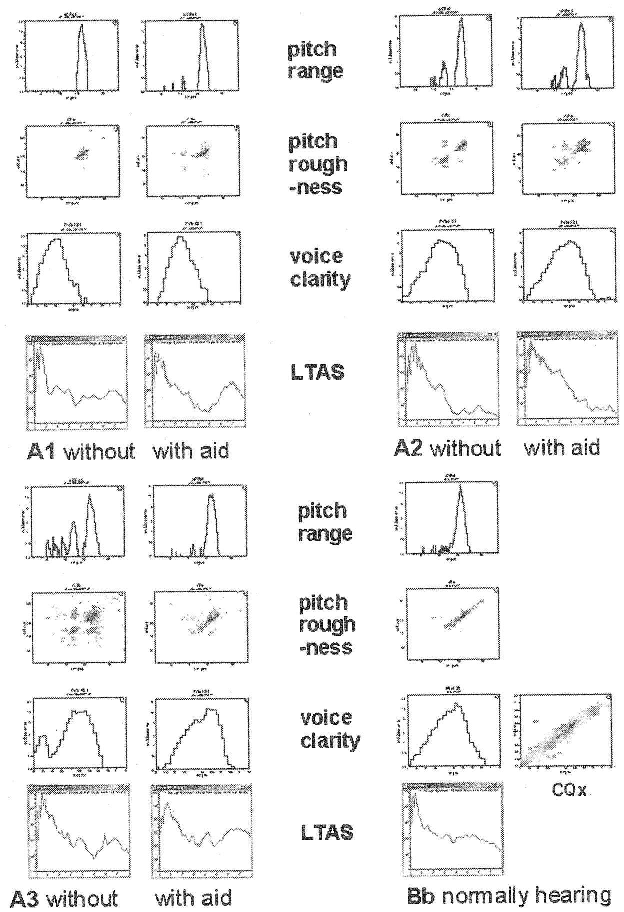

Figure 5 Analyses for girls with CI and one normally hearing boy, Bb. Three sets of thumbnail analyses give overviews of the speech with aid and without aid of three CI users. A fourth set shows the analyses for a normally hearing boy aged 9 years 6 months. It is worth noting that his pitch range is comparable with that of the children who use CIs, but his pitch roughness is much smaller, as is also his contact phase irregularity in the CQx thumbnail and in Table 1, where it is listed under IQx. In their different ways, each CI user has achieved improvement in at least one respect by use of his or her aid. All the CI users are, however, on a learning curve that has downs as well as ups. LTAS, long-term average spectra.

intervals between aided and unaided conditions had not shown substantial differences. Indeed, this had been our own experience when, with another group of boys with CIs, we found only small differences in voice production and intonation control with the aid working and the aid switched off even with long representative story recordings. In our present work, however, the recruitment of volunteer children who, with their parents' permission, were willing to make recordings before breakfast at ~6.30 A.M. prior to their normal daily use of their hearing aids, has given a greater degree of experimental control. Even though each child presents with his or her own idiosyncratic voice characteristics, all the children have shown some measurable benefit from the use of their aids. Improvements arising from the individual use of their aids can be seen variously in regard to: voice pitch range; pitch regularity; vocal fold contact phase range; and, but to a lesser extent, contact regularity. Apart from A3, all the children also had higher speech production ratings with their implants (+acoustic aids) in operation[15] (The ratings were made by a small panel of speech and language therapists working in the school). It is evident from Figs. 1, 2 and 5, however, that, with the use of A3's implant, there were physically measurable improvements in her voice control.

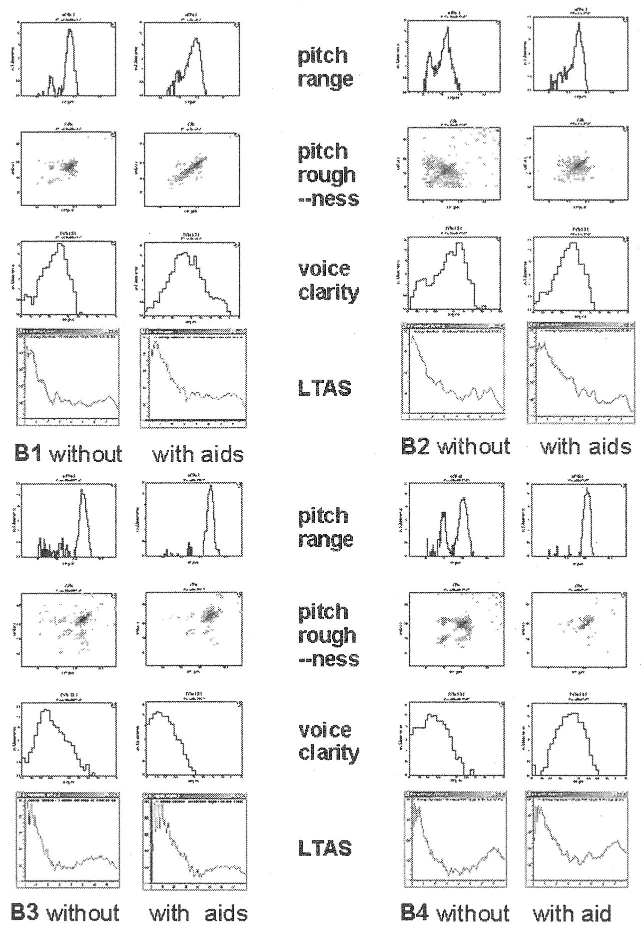

Figure 6 Analyses for boys who use CIs. The four sets of thumbnail plots give an immediate notion of the influence of using a CI aid. For each of these boys, there is an obvious improvement in pitch roughness with somewhat better-defined diagonals. Apart from B1, who has the best improvement in pitch roughness, all the boys have improved pitch range plots. This, however, requires interpretation, because B2 and B4 have voices that are breaking and the use of the aids enables them for the time being to keep their younger voice pitches. Once more, Bb has a better range of smooth voicing as shown by the pitch roughness plots, and he also has a much better contact phase irregularity (IQx in Table 1). LTAS, long-term average spectra.

At the present stage of speech signal processing, it is a great advantage, for evaluation, to use the combination of acoustic microphone and electrolaryngograph data. This makes it possible to make the measurements that have been described here with their use of vocal fold closure epoch determination and contact phase definition; there is a further advantage that comes from accurate real-time processing. The use of the acoustic and laryngograph sensors provides a powerful tool for interactive training.[13] The immediate and relevant feedback from larynx synchronous real-time displays has proved in practice to benefit both the deaf child and the therapist.[8] The complementary use of the detailed voice analyses described here together with subjective evaluation then give a comprehensive in-depth basis for management and validation.

It is somewhat paradoxical that voice pitch control should be successfully mediated with the present generation of CIs. This is because their signal processing is based on rather coarse spectral analysis and, for some implants, no special attention is given to temporal processing. One should rather expect the spectral aspects of voice control (shown here in terms of contact phase ratio) to be better served than, in fact, they are. Whatever may be the theoretical reasons for this disparity, one practical complaint of many CI users on leaving school to fend for themselves in a hearing world is that they have difficulty in making their voice heard in group situations. The, at least partial, solution to this problem may already be evident. The successful normally hearing speaker has learned to achieve good vocal fold contact, closed phase, control. Good closure duration (Qx), good closure regularity (CQx), and good vocal fold contact rapidity (LTAS) may also, with real-time therapy, all be capable of future achievement by the CI user, hand in hand with intonation improvement.

ACKNOWLEDGMENTS

We thank the parents for allowing us to work with their children and the children for their enthusiastic contributions. We are also grateful for help from Simon Hu at Laryngograph Ltd. and from David Canning. The research would not, however, have been feasible without the support of the speech-language therapy, teaching, and care staff at Mary Hare.

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