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Research Article
**AMBULATORY PHONATION MONITORING IN PRELINGUAL AND
POSTLINGUAL DEAF PATIENTS AFTER COCHLEAR IMPLANTATION**

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Short Title: Phonatory modifications in cochlear implant patients

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1 **Abstract**

2 **Introduction:** Hearing loss is known to play a fundamental role in voice production due to a lack of
3 auditory feedback. In this study we evaluated both fundamental frequency (F_0) and loudness of voice
4 on adult deaf patients subjected to cochlear implantation and we analyzed these results according to
5 the congenital or acquired onset of the deafness.

6 **Methods:** the study population, balanced in terms of sex, consisted of 32 adults who had undergone
7 cochlear implantation due to severe or profound bilateral hearing loss (16 with prelingual deafness
8 and 16 with postlingual deafness) and their outcomes were compared with a control group of 32
9 normal hearing (NH) subjects. All subjects were asked to utter the sustained vowel /a/ for at least 5
10 seconds and then to read an Italian phonetically balanced text. Voice recordings were performed by
11 means of an ambulatory phonation monitoring (APM 3200). Measurements were performed without
12 cochlear implant (CI), then with CI switched on, both in quiet and with background noise.

13 **Results:** compared to NH subjects, deaf individuals were overall characterized by higher F_0 and
14 loudness values, especially in the vowel task than the reading. In the sustained vowel task, no
15 patients demonstrated significant voice changes after switching on the CI; contrarily, in the reading
16 task, the use of the CI reduced both loudness and F_0 up to values comparable to NH subjects,
17 although only in males. There was no significant difference in speech parameters between prelingual
18 and postlingual deafness, although overall lower values were evident in case of postlingual deafness.
19 The use of the CI showed a significant reduction of F_0 in males with postlingual deafness and of
20 loudness, both for patients with prelingual and postlingual deafness. Finally, there was a positive
21 correlation between postoperative hearing thresholds and overall speech loudness, highlighting how
22 subjects with better hearing outcomes after CI positioning generally speak with a lower loudness and
23 therefore a reduced vocal effort and load.

24 **Discussion/Conclusion:** we found similar speech performances between prelingual and postlingual
25 deafness, both in the vowel /a/ phonation and in the reading, providing a further suggestion that
26 prelingual adult patients may benefit from cochlear implantation in phonation as well, in addition to
27 the known excellent hearing outcomes. Overall, these results highlight the ability of the CI to adjust
28 in everyday speech certain phonatory aspects such as F_0 and loudness by restoring the auditory
29 feedback.

30

31 **Introduction**

32 People with hearing loss are more likely to suffer from voice and speech disorders than those with
33 normal hearing (NH) due to their poor auditory feedback mechanisms. Auditory feedback is an
34 internal communication loop that helps speakers, using the sensory information acquired while the
35 task is in progress, to self-monitor and adjust their voice during phonation [Ubrig et al., 2019]. NH
36 individuals commonly exhibit robust control of speech and adapt their vocal production to
37 compensate for competitive acoustic scenarios, such as in presence of background noise where the
38 Lombard effect happens, and speakers raise vocal loudness to be heard and intelligible [Lee et al.,
39 2017]. In case of severe hearing loss, the poor auditory feedback mechanisms may determine vocal
40 alterations, such as increased pitch and loudness variability, as well as problems in managing speech
41 intensities and intelligibility, thus compromising social interactions. Extensive literature
42 demonstrates that the use of a cochlear implant (CI), i.e., an electronic device that is surgically
43 implanted in the inner ear directly stimulating the auditory nerve fibers to provide sound sensation,
44 in addition to all the hearing benefits, provides advantages for voice production by restoring the
45 auditory feedback [Wilson et al., 1991; Coelho et al., 2009]. In particular, the main findings in adults
46 are related to the reduction of vocal pitch/fundamental frequency (F_0) and speech loudness (sound
47 pressure level, SPL) [Schenck et al., 2003; Perkell et al., 2007; Ubrig et al., 2019; Gautam et al., 2019],
48 which in turn imply a reduced effort, as well as a variable decreasing of both jitter (pitch variability)
49 [Evans and Deliyski, 2007; Gautam et al., 2019] and shimmer (amplitude variability) [Hocevar-
50 Boltezar et al., 2006; Gautam et al., 2019]. Other parameters investigated were related to the
51 improved phonatory control of vowels and consonants by reducing variability [Langereis et al., 1997;
52 Schenck et al., 2003] and the decreased speech timing duration [Gautam, 2019]. However, evidence
53 so far is limited in considering mainly speech production with CI in postlingually adult deaf patients
54 or prelingually deaf children. To the Authors' knowledge, only Evans reported phonatory data about
55 prelingual adult deaf [Evans and Deliyski, 2007].

56 In addition, most of the studies focusing on speech production in CI patients evaluated phonation
57 with only simple vocal tasks and in quiet condition, although they confirm how strongly the latter is
58 influenced by the restoration of auditory feedback [Schenck et al., 2003; Wang et al., 2017; Gautam
59 et al., 2019; Ubrig et al., 2019]. This approach does not provide sufficient scientific understanding
60 about speech production in real communication scenarios such as noisy environments. Again, to the
61 Authors' knowledge only Lee reported the effect of background noise on speech modifications after
62 cochlear implantation, although only in postlingually deaf patients [Lee et al., 2017].

63 Furthermore, despite many authors have analyzed voice quality modifications in subjects with
64 profound hearing loss treated with CI, all studies evaluated only a short-lasting phonation consisting
65 in the repetition of single words or vowels protracted for few seconds at a comfortable pitch and
66 constant amplitude [Hocevar-Boltezar et al., 2006; Lee et al., 2017; Upadhyay, 2019]. The only
67 authors who implemented the reading of sentences or short texts in his vocal assessments were
68 Ubrig, although limited to postlingually deaf adults [Ubrig et al., 2019], and Ruff, who evaluated text's
69 reading both in adults and children but only focusing on the evaluation of the reading difficulty and
70 words recognition after cochlear implantation [Ruff et al., 2017].

71 The above-mentioned studies carried out voice recordings through unidirectional or multidirectional
72 microphones, normally positioned from 4 cm to 8 cm from the speaker's labial commissure and at an
73 angle of 45°, with the participants remaining seated during recordings [Hocevar-Boltezar et al., 2006;
74 Ubrig et al., 2019; Upadhyay, 2019]. Possible drawbacks of such kind of evaluations consist in the
75 potential for picking up unwanted environmental sounds, including the speech of others or no
76 volitional voice use such as throat-clearing or coughing, and the alteration of the speech signal due to
77 the influence of supraglottal vocal tract resonances [Cheyne et al., 2003]. Moreover, the inevitable
78 variability of the instruments used for the analysis makes it difficult to interpret and perfectly match
79 the data.

80 The purpose of the present study was thus to track changes of phonatory parameters in adult
81 patients with CI with the high accuracy of a portable vocal dosimeter as the Ambulatory Phonation
82 Monitoring (APM) [Hillman et al., 2006; Cantarella et al., 2014]. This instrument, although not
83 specifically designed for this purpose, has proven indeed to be insensitive to background noise and to
84 provide reliable data on vocal parameters such as F_0 and sound pressure level, rather than those
85 acquired at common unidirectional or multidirectional air microphones included in previous studies
86 [Svec et al., 2005; Mozzanica et al., 2019]. Another strength of this study, which differentiates it from
87 any other similar in literature, concerns the inclusion in the group under examination of postlingual
88 deaf, who have been poorly evaluated so far, in addition to prelingual deafened adults and, above all,
89 the assessment of reading a full text besides to the simple sustained vowel emission.

90 Finally, the analysis of the CI effect was performed by measuring different listening conditions (i.e.,
91 quiet condition and in presence of background noise) allowing for the speculation on the usefulness
92 of phonation measurements as a tool for evaluating the success of the cochlear implantation in
93 relation to the time of onset of the hearing loss.

94 **Materials and Methods**

95 An observational cross-sectional study was conducted in a tertiary care center with a regular CI
96 program. The study was conducted from January 2020 to December 2021 and all clinical data were
97 taken from the CI registry maintained at the institution. The study was carried out according to the
98 Declaration of Helsinki and it was previously approved by the Institutional Review Board (clinical trial
99 n. 3546).

100 Population

101 The study population, balanced in terms of sex, consisted of adults who had undergone cochlear
102 implantation due to severe or profound bilateral hearing loss as per the institute's candidacy criteria
103 (pure-tone average hearing threshold > 75 dB HL at 500 Hz, 1000 Hz and 2000 Hz, and a free-field
104 speech perception threshold equal to or lower than 50% with the best possible amplification through
105 hearing aid in the ear to be implanted) [Quaranta et al., 2009]. The hearing loss was both congenital
106 (prelingual deafness) and acquired (postlingual deafness). Exclusion criteria were: reading limitation
107 of any origin, speech disorders due to malformation, acquired damages to the speech organ, motor
108 speech disorders, voice disorders of any origin besides deafness, difficulties in auditory rehabilitation
109 or CI fitting, associated disabilities.

110 A cohort of 32 patients with CI have been thus included in the study: 16 males (8 prelingual and 8
111 postlingual) and 16 females (8 prelingual and 8 postlingual). Mean age of the patients was 49.7 ± 6
112 years (range 19-81 years of age). Mean preoperative pure tone average (PTA), evaluated in free-field
113 at speech frequencies (0.5 - 1- 2 - 4 kHz) resulted to be equal to 78.5 ± 7 dB HL, whereas mean post-
114 implantation PTA resulted to be equal to 27.3 ± 8 dB HL. Among patients with CI, 26 of them
115 underwent a bilateral cochlear implantation (81%) whereas the remaining six patients had a
116 unilateral CI (19%). All surgeries were performed by the same senior surgeon. Among the patients
117 with unilateral CI, four of them had a bimodal hearing restoration (CI and contralateral hearing aid).
118 The manufacturers of the CIs implanted were Advanced Bionics (4 subjects, 13%), Cochlear (18
119 subjects, 56%) and Med-El (10 subjects, 31%). All the patients with CI underwent auditory
120 rehabilitation after cochlear implantation, had at least 2 years of regular CI mapping after processor's
121 activation and were therefore considered stable from a hearing rehabilitation point of view.

122 A control group composed by 32 normal hearing (NH) subjects (16 males and 16 females), aged
123 between 20 and 64 years old (mean 29.7 ± 3 years) was enrolled. All the NH subjects demonstrated a
124 PTA ≤ 15 dB HL (mean 9.18 ± 4 dB HL). Each subject enrolled in the study gave his/her written
125 informed consent.

126 Measurement procedure

127 Preliminary room acoustic measurements were carried out aiming at assessing whether the
128 reverberation time (RT_{60}) of the selected space, namely the time taken for a signal to decay the full
129 60 dB from its initial level, was suitable for the administration of the test. The evaluations were
130 performed in compliance with the EN ISO 3382-1 standard [ISO, 2009], applying the interrupted
131 noise method through a sound level meter (Acoustilyzer AL1) and a pink noise generator (Minirator
132 MR-1) connected to the main speaker. As the testing room was acoustically treated and had a
133 volume below $45m^3$, the measured RT_{60} was below 0.5 s at medium frequencies and thus the
134 environment was considered acoustically suitable for the purpose of the study.

135 In order to evaluate the spectral and loudness modification of voice in terms of F_0 and sound
136 pressure level, respectively, according to different hearing conditions, NH subjects and patients with
137 CI and were asked to utter the sustained vowel /a/ for at least 5 seconds and to read a brief text in
138 Italian named “Il ramarro della zia”, which is a phonetically balanced content created by Vernero and
139 Schindler in 1998 for speech therapy purposes [Vernero et al., 1998]. NH subjects performed these
140 tasks both in a quiet condition and with a background energetic masking noise of 50 dBA. Similarly,
141 patients with CI performed these tasks twice, both in a quiet condition and with the same
142 background noise of 50 dBA. First, they were asked to switch off their CI; second, they were asked to
143 switch on their CI.

144 Background noise was artificially added using three calibrated loudspeakers, controlled by an
145 audiometer and placed at a standard ear-height (1 meter from the floor) and at the same distance
146 from the receiver (2 meters) in order to obtain the maximum possible masking (one loudspeaker at
147 0° and the lateral ones placed with an angle of 110°).

148 CI patients and NH subjects were sat in a comfortable position. Among CI patients wearing
149 processors in which it was possible to adjust the direction of the microphone, a fixed orientation
150 stimulating the pinna was chosen, which is the most similar condition to NH. Furthermore, the
151 adaptive microphone adjustment function of the CIs, capable of suppressing background noise, has
152 never been selected to avoid any facilitation in the intelligibility of the patient’s voice. In addition, in
153 the four patients who had a bimodal hearing restoration, the hearing aid was always removed during
154 the recordings.

155 Voice recording

156 In order to provide an objective measurement of voice characteristics, the ambulatory phonation
157 monitoring used in the study was the APM model 3200 (KayPENTAX, Lincoln Park, NJ). It consists of
158 an accelerometer, placed adhesively along the anterior part of the neck, which measures the

159 vibrations from the vocal folds through the tissues of the neck and converts them into sound
160 pressure levels (SPL, in dB) of speech. The APM gathers acoustic voice raw data at a rate of 20
161 samples per second and these data are transferred to a microprocessor unit worn in a waist pack.
162 Among the multiple parameters acquired by the APM, it was decided to collect:

163 - Average F_0 (in Hz): expresses the mean frequency at which the vocal folds vibrate.

164 - Average loudness in terms of emitted sound pressure level (in dB): expresses the mean value of the
165 amount of energy of the voice sound wave.

166 Phonation measured in this way has been shown to be relatively insensitive to surrounding sounds
167 and to differentiate volitional voice from other behaviors, such as throat clearing or coughing
168 [Hillman et al., 2006; Mozzanica et al., 2019].

169 Before starting the real voice monitoring, a calibration of the acquisition system was needed subject-
170 by-subject. As the contact sensor placed at the jugular notch needs to provide referred SPL values, in
171 fact, a comparison calibration with respect to an air-microphone (placed exactly 15 cm from the
172 speaker's mouth) was thus performed. In this way, after acquiring together referred SPL values from
173 the air-microphone and voltage levels from the contact sensor due to the skin acceleration
174 generated by the vocal folds' vibration, a calibration function containing subject-related constants
175 could be obtained and then applied while monitoring the real voice. All 64 participants were thus
176 initially asked to perform such calibration procedure, which in practice consisted in the vocalization
177 of a sustained vowel /a/ at increasing loudness levels, from whispers to screams in order to produce
178 all the possible loudness levels produced in the subsequent monitoring. The time required to
179 calibrate the APM never exceeded 5 minutes and all the patients well tolerated the APM device
180 during the evaluations.

181 Statistical Analysis

182 Statistical analysis was performed using SPSS 24.0 statistical software for Microsoft Windows (SPSS,
183 Inc., Chicago, IL). Preliminary analyses were performed to ensure any violation of the assumptions of
184 normality, linearity and homoscedasticity. Variables were compared by means of nonparametric
185 tests due to non-normally distributed data, in particular the Wilcoxon signed rank test and the Mann-
186 Whitney U test for non-independent and independent samples respectively. Analysis of variance was
187 performed with Kruskal-Wallis test and correlations were assessed by means of Spearman's Rank
188 Order Test. Two-sided exact tests were used and p values $< .05$ were considered significant.

189 **Results**

190 A Mann-Whitney U test was conducted to compare the post-implantation PTA scores according to
191 the gender, the laterality of the CI and the onset of the deafness. There was no significant difference
192 in postoperative PTA values between males and females ($p = .138$), between unilateral and bilateral
193 cochlear implantation ($p = .524$) and between congenital and acquired deafness ($p = .491$). Based on
194 these similarities between groups in terms of postoperative auditory results, we found it appropriate
195 to consider all patients similar to each other and therefore valid and significant the outcomes of the
196 phonatory tests. Similarly, there were no significant differences between males and females
197 concerning the age, as well as between unilateral and bilateral CI ($p < .05$); on the contrary, patients
198 with prelingual deafness resulted significantly younger (mean 42.5 years old, $n = 16$) compared to
199 postlingual deafness (mean 62.5 years old, $n = 16$), $p < .001$.

200 The speech F_0 and loudness values obtained from both control subjects and CI recipients are
201 reported in Tables 1 to 3.

202 The Kruskal-Wallis test did not reveal any statistically significant difference between speech
203 characteristics of the CIs belonging to the three different CI companies (Advance Bionics, $n = 4$;
204 Cochlear, $n = 10$; MedEl, $n = 18$; $p > .05$), neither as regards the speech F_0 values nor for the loudness.

205 **1. Sustained Vowel Task**

206 The Kruskal-Wallis test revealed a statistically significant difference in F_0 values across NH male
207 subjects ($n = 16$), deaf males without CI ($n = 16$) and deaf males with CI on ($n = 16$), $p = .001$. The deaf
208 males with CI switched off demonstrated higher F_0 scores than the other two groups. A similar
209 difference across these three groups was also demonstrated for females ($p = .001$), with significantly
210 higher F_0 values in patients with CI switched off compared to women with CI on and NH women. A
211 statistically significant difference at Kruskal-Wallis test was also demonstrated concerning the vowel
212 /a/ loudness values between NH subjects ($n = 32$), patients with CI switched off ($n = 32$) and patients
213 with CI turned on ($n = 32$), $p = .031$. Deaf patients without the use of the CI demonstrated higher
214 loudness values as compared to the other two groups. Among deaf patients, the Wilcoxon Signed
215 Rank test revealed a slight decrease of F_0 values, although not statistically significant, following the
216 activation of the CI, both in males ($p = .278$) and females ($p = .352$). Likewise, there were no
217 significant differences in loudness values in the vowel task after CI activation ($p = .286$).

218 The Mann-Whitney U test was furthermore used to compare both F_0 and loudness of the vowel task
219 between prelingual and postlingual deafness. In particular, males with prelingual deafness showed
220 lower F_0 values, although not statistically significant, than males with postlingual deafness, both with
221 CI off ($p = .781$) and with CI on ($p = .486$). Contrarily, females with prelingual deafness demonstrated

222 higher F_0 values, although not statistically significant, than females with postlingual deafness, both
223 with CI off ($p = .376$) and with CI on ($p = .133$). As regards the loudness, higher though not
224 significantly different values were reported in prelingual patients compared to postlingual ones, both
225 with CI off ($p = .174$) and with CI on ($p = .250$).

226 The switching on and therefore the use of the CI has not shown, at paired-samples t-test, to
227 significantly modify the values of F_0 and loudness in the vowel task, both in case of prelingual and
228 postlingual deafness ($p > .05$) (Table 4).

229 **2. Reading Task**

230 Concerning the NH subjects, a statistically significant increase in speech loudness was reported
231 following the addition of background noise at 50 dBA of intensity when reading the text “Il ramarro
232 della zia” ($p < .001$). Similarly, a significant increase of the F_0 scores in the reading with background
233 noise was shown in both NH males and females ($p < .001$ at Wilcoxon Signed Rank test).

234 Similarly, deaf patients' speech evaluation with CI on demonstrated a significant increase of the F_0
235 values when a background noise was added, both in males and females ($p = .007$ and $p = .008$
236 respectively), and a similar significant increase of values was also shown for loudness with respect to
237 the assessment in quiet conditions ($p < .001$).

238 The Mann-Whitney U test showed, in males and in quiet conditions, significantly higher F_0 values in
239 deaf patients with CI off than in NH subjects ($p = .035$) and subsequent activation of CI highlighted a
240 significant reduction in these same values ($p = .023$ at Wilcoxon Signed Rank test), with outcomes
241 that have become comparable to the F_0 of NH subjects ($p = .184$). In contrast, there was no
242 significant difference between female NH subjects and female deaf with CI switched off ($p = .402$),
243 and the further switching on of the CI did not significantly affect the F_0 in female patients ($p = .717$).

244 As regards the speech loudness in quiet, there was no significant difference in values between NH
245 subjects and deaf patients with CI switched off ($p = .989$), whereas a statistically significant reduction
246 of the values was demonstrated in the same deaf patients after CI activation ($p < .001$).

247 NH subjects showed similar values between the sustained vowel task and the reading task as for
248 loudness ($p = .640$) and the F_0 in females ($p = .717$), while in NH men the average F_0 value resulted
249 significantly lower in the phonation of the vowel /a/ ($p = .008$). Conversely, deaf patients with CI off
250 showed significantly higher F_0 values ($p = .003$ for females and $p = .026$ for males) and loudness
251 values ($p < .001$) in the vowel task than in the reading task.

252 The relationship between PTA values and speech characteristics of deaf patients was investigated
253 using Spearman correlation coefficient. By analysing the reading task with and without CI, there was
254 no significant correlation between mean post-implantation PTA thresholds and F_0 values, both for
255 males and for females ($p > .05$); similar results were also obtained by assessing the vowel task ($p >$
256 $.05$). On the contrary, there was a positive correlation between mean PTA thresholds and speech
257 loudness, both with CI off ($r = .36, p < .05$) and CI on ($r = .35, p < .05$): higher speech loudness values
258 resulted associated with higher PTA thresholds.

259 Furthermore, in the reading task, there was a negative correlation between the age of deaf patients
260 and their mean F_0 scores, in both genders and with CI on ($r = -.31, p < .05$), with higher F_0 scores
261 detected in younger patients. Contrarily, any other correlation between speech characteristics and
262 patients' age was found, as they all resulted to be not significant ($p > .05$).

263 Further comparative analyses carried out on the reading task between prelingual and postlingual
264 subgroups showed lower F_0 values in all patients with postlingual deafness, both male and female,
265 both with and without CI, although this difference was only statistically significant in deaf women,
266 without the use of the CI ($p = .047$). Lower though not statistically significant values were also
267 demonstrated in case of postlingual deafness concerning the speech loudness, both with CI off and CI
268 on ($p > .05$). Furthermore, we did not report any significant difference in speech characteristics
269 between prelingual or postlingual deafness when speech was assessed with background noise ($p >$
270 $.05$).

271 The switching on of the CI showed to significantly reduce the F_0 values only in males with postlingual
272 deafness ($p = .011$), whereas there were no differences among males with prelingual deafness or in
273 females after CI activation ($p > .05$). On the contrary, the use of the CI demonstrated a significant
274 decrease in the speech loudness values in all patients ($p < .05$), both in cases of prelingual and
275 postlingual deafness (Table 5).

276 **Discussion/Conclusion**

277 The aim of the present study was to evaluate the voice modifications in adults with profound hearing
278 loss following cochlear implantation, particularly focused on differences between prelingual and
279 postlingual deafness. Our study group consisted of 32 profoundly deaf adults who underwent
280 cochlear implantation, equally distributed between males and females, and between prelingual and
281 postlingual deafness. A control group composed by 16 normal hearing females and 16 normal
282 hearing males was also involved. Both groups undergone voice recordings consisting in the reading a
283 phonetically balanced passage while being equipped with a contact-sensor based voice monitoring

284 device (i.e., the APM device by KayPENTAX). From the monitoring, mean fundamental frequency and
285 sound pressure level were extracted for each participant, both in quiet and in noise conditions.

286 *The role of cochlear implantation and subjective features in voice production*

287 It is well recognized how hearing loss plays a fundamental role in vocal production. Patients with
288 congenital deafness, although submitted to cochlear implantation, frequently manifest pronunciation
289 errors, vowel substitutions and difficulties in intonation, resulting in very unintelligible speech
290 [Hocevar-Boltezar et al., 2006; Lenden and Flipsen, 2007]. Similarly, even those subjects who
291 experience the occurrence of deafness as adults demonstrate a degradation of the speech over time
292 and the restoration of the auditory feedback by CI has been shown to induce adjustments in speech
293 production, particularly in the reduction of the fundamental frequency and the speech loudness
294 [Ubrig et al., 2011; Coelho et al., 2012; Gautam et al., 2019; Ubrig et al., 2019; Boisvert et al., 2020].
295 However, as stated by Coelho in her systematic review of the literature, controversial results and the
296 heterogeneity of the methods used in most studies makes it difficult to understand the real effect of
297 the CI on deaf patient's speech [Coelho et al., 2012]. To the Authors' knowledge, only Ubrig analyzed
298 a large case series, comparable to the one considered in the present study, although he took in
299 consideration exclusively adults with postlingual deafness [Ubrig et al., 2011].

300 Consistent with the congenital onset of deafness and the related need to restore the auditory
301 feedback earlier, the mean age of the prelingual deaf group was significantly lower (42 years old)
302 than patients with late acquired deafness (62 years old). Nonetheless, a very satisfactory mean
303 postoperative PTA threshold (27.3 dB HL in free-field assessment) was achieved in all patients, with
304 no significant differences in hearing thresholds depending on gender, unilateral or bilateral
305 implantation, and between prelingual or postlingual deafness. Indeed, although numerous studies
306 suggest an early cochlear implantation in deaf prelingual children, no age-dependent difference in
307 the electrically evoked action potential of the auditory nerve has been demonstrated after cochlear
308 implantation [Harrison et al., 2005] and Canale reported no differences in perceived quality of life or
309 benefit of the CI between prelingually and postlingually deafened groups [Canale et al., 2016].
310 Furthermore, recent findings suggest that the good results of the CI in adults depend not only on the
311 duration of sound deprivation, but also on the extent of the rehabilitation carried out in childhood:
312 all our patients had previously undergone adequate oral rehabilitation and they had long used a
313 bilateral hearing aid in case of auditory residuals [Canale et al., 2019].

314 Hillman showed that a vocal accelerometer provides superimposable data of F_0 , vocal loudness and
315 phonation time to those recorded by a traditional microphone, both in control subjects and in
316 individuals with mild and severe dysphonia [Hillman et al., 2006]. Furthermore, Švec demonstrated

317 that the APM can provide the average SPL value of soft, comfortable, or strong voices with an
318 accuracy higher than ± 2.8 dB in 95% of cases, even more accurate than microphones [Svec et al.,
319 2005]. This is in agreement with Astolfi et al. who found, for other contact-sensor based devices, a
320 significant advantage in using a contact microphone despite its higher uncertainty [Astolfi et al.,
321 2018]. Indeed, although a headworn air microphone provides an uncertainty of up to 2 dB and a
322 contact-sensor based device of up to 3 dB, the latter neglects the presence of background noise –
323 even of high magnitudes – and allows for long-term, accurate and repeated monitoring. To date, only
324 Mozzanica included the APM in voice production assessment after cochlear implantation, although
325 related to the registration of a 24-hours working day and limited to postlingual deafness [Mozzanica
326 et al., 2019]. Our voice recordings included the prolonged emission of the vowel /a/ at habitual pitch
327 and loudness, which was chosen because mainly dependent on acoustic rather than orosensitive
328 control [Svirsky et al., 1991]. However, with the aim of evaluating the speech in a condition as close
329 as possible to everyday life, we also included the reading of a phonetically balanced text, both in
330 quiet conditions and with a background noise of 50 dBA.

331 To date, except for a study by Lee [Lee et al., 2019], the speech characteristics of deafs with CI have
332 never been evaluated in competitive acoustic conditions but always only with simple vocal tasks and
333 in quiet [Hocevar-Boltezar et al., 2006; Evans and Deliyski, 2007; Wang et al., 2017; Ubrig et al., 2019;
334 Upadhyay et al., 2019], therefore not providing a sufficient understanding about speech production
335 in real communication conditions and noisy environments. Our results showed, as predictable, a
336 significant increase of both F_0 and loudness in the reading task with background noise, which was
337 evident in both NH subjects and deaf patients with CI on. Similar outcomes, although limited to
338 postlingual deafness, were confirmed by Lee as patients with CI seem to respond to background
339 noise by adjusting speech production accordingly, as a potential perceptual benefit of the Lombard
340 effect which works regularly in NH subjects, and which is properly restored with CI turned on [Lee et
341 al., 2017].

342 In the comparison between the vowel and the reading tasks, NH females were shown to maintain
343 both F_0 and loudness relatively steady, whereas NH males showed similar loudness but significantly
344 lower F_0 values in the vowel task. As far as the steadiness of voice loudness is concerned, and
345 assuming that the vowel uttering and the text reading are two successive voice production tasks, the
346 obtained results corroborate a study by Castellana et al. who found that NH subjects exhibit a low
347 intra-speaker variability within 1 dB for equivalent and mean sound pressure levels, and below 2 dB
348 for mode sound pressure level [Castellana et al., 2017]. On the contrary, all deaf patients
349 demonstrated higher F_0 and loudness values in the vowel task compared to the reading. A very useful

350 review of the literature by Borden suggests that a very short auditory information is not sufficient for
351 motor control centers to simultaneously regulate speech production [Borden, 1979]. Otherwise, a
352 reading, lasting about one minute, allows the subject more time to analyze his speech and possibly
353 make a correction of its parameters.

354 The role of CI activation

355 Similar results were also found in relation to CI activation, highlighting its role in bringing a change in
356 the way voice is handled by patients. After switching on the CI in the sustained vowel task, despite a
357 slight but not significant reduction in F_0 and loudness values, the whole sample of deaf patients did
358 not show the expected voice modifications presumably due to the sudden change in auditory
359 feedback. As mentioned by Gautam, indeed, vocal control may not be sometimes dependent on
360 moment-to-moment feedback but over longer time scales, thus not allowing sufficient vocal
361 adaptation in case the CI is switched on and off within a few minutes and in case the task is too short
362 [Gautam et al., 2019]. In this regard, we highlighted heterogeneous and discordant results in
363 literature: Monini reported a significantly reduced F_0 in the voice samples of the Italian vowel /a/ at
364 an early stage after cochlear implantation, although adults and children were assessed together
365 [Monini et al., 1997]. Differently, Kirk and Edgerton reported, in the vowel /a/ assessment, lower F_0
366 values and a reduced variability of loudness level only on male patients, whereas females showed
367 higher F_0 and an increasingly variable loudness with CI on [Kirk and Edgerton, 1983].

368 As for the reading of the text, the switching on of the CI seems able to significantly reduce both
369 loudness and F_0 in deaf men, up to values comparable to NH subjects: this result is consistent with
370 the observations of Hamzavi et al. whose CI patients tended to have lower F_0 postoperatively
371 approaching the normal range of F_0 [Hamzavi et al., 2000]. Leder, in this regard, demonstrated that
372 when adequate auditory feedback is restored with cochlear implantation, the F_0 is the first acoustic
373 characteristic to approximate normal values again and that was particularly evident in men [Leder et
374 al., 1987]. Conversely, the CI activation caused overall no significant changes of the F_0 values in deaf
375 women during the reading task. Such a great variability of frequency among deaf subjects can be
376 found in all the very few works proposed so far in the literature on the subject, approximately all
377 discordant with each other in the results and mostly focused on pediatric population [Borden, 1979;
378 Kirk and Edgerton, 1983; Hamzavi et al., 2000; Coelho et al., 2009].

379 The analysis of the vocal characteristics of the patients did not allow to highlight any significant
380 difference in the phonatory outcome between CI recipients from different manufacturers. Since the
381 hearing perceived by any type of hearing aid is certainly also characterized by a relevant subjective
382 component, it is very complex to compare the hearing outcomes between two different CI

383 companies; however, as in our study, Withers previously found no differences in PTA and speech
384 perception in a case of bilateral cochlear implantation using different devices, although patients'
385 opinions on perceived sound quality significantly differed [Withers et al., 2011]. In fact, although any
386 CI of each company has unique technical features and heterogeneous hearing outcomes have been
387 frequently described in literature depending on CI specific features, any device, if properly implanted
388 and correctly functioning, is able to improve hearing and thus determine a restoration of the
389 auditory feedback. Therefore, we can conclude that the previously described speech modifications in
390 terms of F_0 and loudness are exclusively related to the simple use of the device and not to the model
391 or the brand of the CI adopted.

392 *The role of prelingual and postlingual deafness*

393 The period of onset of the deafness is known to affect speech as early deprivation of auditory
394 feedback affects F_0 control and articulation accuracy, just as people with prelingual deafness have
395 difficulty learning to speak intelligibly [Ruff et al., 2017]. Nonetheless, although lower values of both
396 F_0 and loudness in postlingual deafness, we had no significant differences between speech
397 characteristics of prelingual and postlingual deaf patients, both in the sustained vowel task and in the
398 reading task, as also the speech quality of postlingual deaf decreases due to a lack of adequate
399 auditory feedback. The only exception was reported for females, whose subjects with postlingual
400 deafness showed significantly lower F_0 values than deaf females with prelingual deafness.

401 Similar results were also reported after CI activation, both in the vowel phonation and in the reading,
402 with no differences between prelingual and postlingual deafness. We can therefore affirm that,
403 although different postoperative auditory results are reported in the literature depending on the
404 period of onset of the hearing loss, almost all deaf patients behave in a similar way from the
405 phonatory point of view, whatever the nature (prelingual or postlingual) of their deafness.

406 Moreover, the further addition of background noise to speech assessments performed on CI
407 recipients did not demonstrate significant differences in their phonatory characteristics, both in case
408 of prelingual and postlingual deafness.

409 The analysis of how the patients' speech parameters changed after switching on the CI showed an
410 important reduction in loudness values when reading the passage, both for patients with prelingual
411 and postlingual deafness. Similarly, we found that the application of the CI also plays a decisive role
412 in modifying the F_0 in patients with postlingual deafness, although this only happens in males.

413 Different outcomes were reported by Smoorenburg in the evaluation of speech samples before and
414 one to four years after cochlear implantation: although analyzing only postlingual deafness, he

415 noticed that abnormally high pitches of deafs decreased after CI in some of the implanted women
416 but not in men [Smoorenburg et al., 1994].

417

418 Overall, these results highlight the ability of the CI to adjust certain phonatory aspects such as
419 fundamental frequency and loudness in most deaf patients simply by restoring auditory feedback,
420 thus improving their vocal experience in whatever acoustic conditions they wish to communicate. A
421 future development of this study will certainly be the analysis of further qualitative aspects of voice
422 production after CI application as pitch strength, cepstral peak prominence smoothed, acoustic voice
423 quality index, jitter, shimmer, and harmonics-to-noise ratio.

424 The significant positive correlation that emerged between postoperative hearing thresholds and
425 speech loudness confirmed that subjects with better hearing outcomes after CI activation generally
426 speak with a lower loudness, which literature has shown to turn in a reduced vocal effort and load
427 [Bottalico et al., 2012; Puglisi et al., 2017].

428 Furthermore, the negative correlation found between overall patients' age and speech F_0 values
429 highlighted how older deaf patients, whether males or females, generally speak with a lower F_0 when
430 the CI is on, both in quiet conditions and in the presence of background noise. This result agrees with
431 past studies, although conducted only on normal hearing listeners, as F_0 tended to decrease
432 markedly in association with aging [Nishio and Niimi, 2008]. Such correlation could be explained not
433 only by the simple application of the CI but also by the reduced speed of cognitive processing with
434 advancing age: a slowdown of specific executive cognitive resources, such as working memory, is
435 known to influence several top-down mechanisms, one of which could also be phonation [Zucca et
436 al., 2022].

437 The strength of this study, which constitutes a step forward with respect to previous papers in
438 literature, was the accurate evaluation of speech characteristics by means of a portable vocal
439 dosimeter as the APM model 3200. As far as the practical outcomes obtained in this work, the main
440 conclusions can be summarized as follows:

- 441 • Similar speech performances between prelingual and postlingual groups, both in the vowel
442 /a/ phonation and in the reading of the text were found.
- 443 • Although poorer auditory outcomes with CI have been commonly demonstrated in adults
444 with congenital hearing loss due to sound-deprived history and longer post-operative
445 rehabilitation, our result provides a further suggestion that prelingual adults patients may
446 benefit from cochlear implantation.

447 • Since for the purposes of a correct mapping of the CI it is important for the patient to have a
448 good perception of the loudness variations, particularly in order to precisely balance the
449 electrodes, an auditory rehabilitation aiming to control the loudness and the frequency of
450 one's own voice would force the patients to self-listen to himself. Consequently, with self-
451 listening, the subject would improve his discriminative capacity and therefore his acoustic
452 accuracy for the purposes of the CI mapping.

453

454 **Statements**

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459

460 **Statement of Ethics**

461 The study was approved by the bioethics institutional review board of the University of Turin
462 (approval number 3546).

463 The study was conducted in accordance with the ethical standards of our institution and the
464 principles expressed in the Declaration of Helsinki.

465 Written informed consent to participate in the study was obtained from all participants.

466

467 **Conflict of Interest Statement**

468 The authors have no conflicts of interest to declare.

469

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472

473 **Author Contributions**

474 Andrea Albera, Giuseppina Emma Puglisi and Andrea Canale performed measurements, analyzed
475 data and wrote the paper; Arianna Astolfi and Francesco Mozzanica designed the study, Giuseppe
476 Riva and Claudia Cassandro provided statistical analysis and critical revision.

477

478 **Data Availability Statement**

479 All data generated or analyzed during this study are included in this article. Further enquiries can be
480 directed to the corresponding author.

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