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The Effect of Binaural Beamforming Technology on Speech Intelligibility in Bimodal Cochlear Implant Recipients

Jantien L. Vroegop Nienke C. Homans André Goedegebure
J. Gertjan Dingemanse Teun van Immerzeel Marc P. van der Schroeff

Department of Otorhinolaryngology and Head and Neck Surgery, Erasmus Medical Center, Rotterdam, The Netherlands

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Bimodal hearing · Cochlear implant · Hearing aid · Fitting · Binaural beamformer

Abstract
Although the benefit of bimodal listening in cochlear implant users has been agreed on, speech comprehension remains a challenge in acoustically complex real-life environments due to reverberation and disturbing background noises. One way to additionally improve bimodal auditory performance is the use of directional microphones. The objective of this study was to investigate the effect of a binaural beamformer for bimodal cochlear implant (CI) users. This prospective study measured speech reception thresholds (SRT) in noise in a repeated-measures design that varied in listening modality for static and dynamic listening conditions. A significant improvement in SRT of 4.7 dB was found with the binaural beamformer switched on in the bimodal static listening condition. No significant improvement was found in the dynamic listening condition. We conclude that there is a clear additional advantage of the binaural beamformer in bimodal CI users for predictable/static listening conditions with frontal target speech and spatially separated noise sources.

Introduction

Cochlear implant (CI) selection criteria have expanded [Dowell et al., 2016; Leigh et al., 2016] over the last few years. The use of a CI in one ear and a hearing aid (HA) in the contralateral ear, referred to as bimodal hearing, has become standard care. Bimodal hearing has been shown to improve speech recognition and sound localization when compared to unilateral CI use alone [Blamey et al., 2015; Ching et al., 2007; Dorman et al., 2015; Illg et al., 2014; Morera et al., 2012]. However, speech comprehension remains a challenge in acoustically complex real-life environments due to reverberation and disturbing background noises [Lenarz et al., 2012; Srinivasan et al., 2013].

Directional microphones aim to improve the signal-to-noise ratio (SNR) by means of enhancing sounds of interest versus spatially separated interfering sounds [Dillon, 2012]. The most recent development of directional HA technology involves wireless communication, which enables the exchange of audio data received by the microphones of both the left and the right HA. The increase in physical separation between the different microphones can be used to achieve narrow beamforming with further SNR improvements [Lotter and Vary, 2006].

KARGER

E-Mail karger@karger.com
www.karger.com/aud

Jantien Vroegop
ENT Department, Erasmus Medical Center
Postbus 2040
NL–3000 CA Rotterdam (The Netherlands)
E-Mail j.l.vroegop@erasmusmc.nl

However, binaural information is distorted by using this technology. HA studies investigating binaural beamforming have shown a trade-off between improvement in SNR on the one hand, and a deterioration of binaural cues on the other [Kidd et al., 2015; Picou et al., 2014]. The acoustic conditions play a critical role, as more static and/or predictable listening conditions result in more effect of binaural beamforming compared to more dynamic setups [Best et al., 2015; Neher et al., 2017].

Until now, there are no studies evaluating the effect of bilateral beamforming for bimodal CI users. Recently, an HA enabling wireless communication was introduced, offering possibilities for a beamforming algorithm for bimodal hearing. As bilateral directional processing for HA tends to be a trade-off between SNR improvement and binaural cue preservation, the aim of this study was to investigate if, and in what conditions, usage of a binaural directional microphone algorithm would improve the auditory functioning of bimodal CI users. Two settings were used for testing, i.e., reflecting daily life in a static and in a more dynamic setting. We hypothesized that an optimal benefit of the binaural beamformer will be found for the static condition and that suboptimal orientation under dynamic conditions would reduce the benefit obtained from the binaural beamformer.

Methods

Participants

A total of 18 postlingually deafened adults participated in this study; see Table 1 for patient demographics. Participants ranged in age from 32 to 81 years old (mean age 62 [SD 15] years). All were experienced bimodal users, unilaterally implanted with the Advanced Bionics (AB) HiRes 90K implant by surgeons from 4 different CI teams in The Netherlands. All participants had used their CI for at least 6 months prior to this study (mean 4 [SD 3.5] years). All participants used either the AB Naída Q70 or Q90 sound processor in daily life. In the study, all participants used the AB Naída Q90 sound processor to gain access to the bimodal beamforming function "Stereozoom" (Phonak, Sonova Netherlands, Vianen, The Netherlands). In addition, all had open-set speech recognition of at least 70% correct phonemes at 65 dB SPL on the clinically used Dutch consonant-vowel-consonant (CVC) word lists [Bosman and Smoorenburg, 1995] with the CI alone. Only participants with unaided hearing thresholds in the nonimplanted ear of ≥80 dB HL at 250 Hz were included. Figure 1 shows the unaided audiograms of the nonimplanted ear of the individual participants. All participants used an HA prior to the study, which was replaced by the Phonak Naída Link UP HA for the tests in the study. All participants were native Dutch speakers who signed an informed consent letter before participating in the study. The approval of the Ethics Committee of the Erasmus Medical Centre was obtained (protocol No. METC306849).

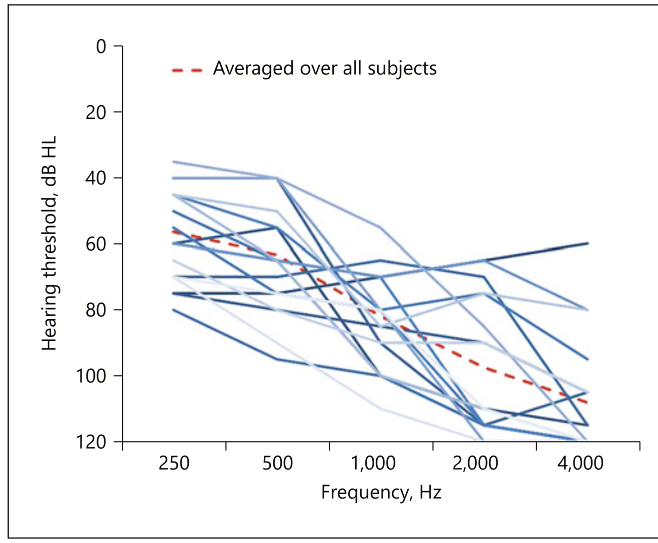

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Fig. 1. The hearing thresholds of the individual participants for the ear with the hearing aid. The dashed line displays the mean hearing loss.

Table 1. Participant demographics, including HA and CI experience

Participant No.	Age, years	Sex	Etiology	HA[a] exp., years	CI exp., years
1	59	M	unknown	21	5
2	49	F	unknown	16	6
3	34	F	familiar	9	4
4	71	M	familiar	17	1
5	62	F	DFNA9	26	4
6	64	F	unknown	20	2
7	69	M	unknown	13	2
8	72	F	unknown	38	12
9	79	M	unknown	25	1
10	48	M	familiar	20	0.5
11	76	F	unknown	16	1
12	48	M	unknown	18	1
13	74	M	Menière	25	9
14	49	M	unknown	27	11
15	68	F	familiar	28	0.5
16	32	M	unknown	31	4
17	57	M	unknown	2	1
18	81	M	unknown	20	2

HA, hearing aid; CI, cochlear implant; M, male; F, female; exp., experience.
[a] Nonimplanted ear.

HA and CI Fitting

The HA was fitted with the Phonak bimodal-fitting formula, a special prescriptive fitting formula for bimodal hearing which was developed for this HA. This formula differs from more standard-

Table 2. Different test conditions

Condition No.	Listening condition	Speaker location
1	cochlear implant only	S0
2	cochlear implant only	S-45/45
3	bimodal	S0
4	bimodal	S-45/45
5	bimodal beamformer	S0
6	bimodal beamformer	S-45/45

fitting formulas in 3 aspects: the frequency response, the loudness growth, and the dynamic compression. Firstly, this formula aims to align the frequency response by optimizing low-frequency gain and bandwidth. Low-frequency gain optimization uses the model of effective audibility to ensure audibility of speech recognition in quiet environments [Ching et al., 2001]. Frequency bandwidth is optimized, making frequencies between 250 and 750 Hz audible [Sheffield and Gifford, 2014], to maximal width [Neuman and Svirsky, 2013], and amplification does not extend into presumed dead regions [Zhang et al., 2014]. Secondly, the loudness growth is aligned by implementing the input-output function of the CI in the HA. Thirdly, the dynamic compression behavior is aligned by porting the Naída CI dual-loop AGC into the HA [Veugen et al., 2016]. The Naída Link HA is able to communicate wirelessly with the AB Naída CI Q90 and Q70. With the Q90, the communication is extended to obtain a narrow binaural beamformer, the Stereozoom. This beamformer combines the 4 omnidirectional microphones from the Phonak Naída Link HA and the AB Naída CI Q90. First, on each side, the 2 microphones are processed to obtain a standard dual microphone system. These directional signals are then exchanged over the wireless link between the HA and the CI. Utilizing a frequency-dependent weighting function, the HA and the CI then linearly combine the ipsilateral and contralateral directional signals to create a binaural directivity. The binaural beamwidth is controlled by the weighting function, and is typically narrower than what a simple monaural 2-microphone beamformer is able to achieve. No fine-tuning of the HA or volume adjustments were performed.

For the test session the participant's current "daily" CI program was used, which was made during clinical programming. The participants had been using their current CI program for 10 months (SD 6 months) on average before the start of the study. The method of CI programming, completed clinically before study participation, was as follows. The upper electrical current levels (M-levels) were set to a most comfortable level for each individual electrode through an ascending loudness judgment procedure. Subsequently, electrodes were checked for equal loudness between them. The minimum current levels (T-levels) were set to threshold levels measured for 0% detection on each individual electrode. Threshold levels were obtained using an ascending presentation, followed by a standard bracketing procedure. After that, the overall level of the M-level profile was adjusted to make live speech sound comfortable and easily understandable. Additional fine-tuning of the T- and M-level profiles were applied based on the feedback of the CI user and the professional judgement of the clinical audiologist. Noise reduction algorithms on

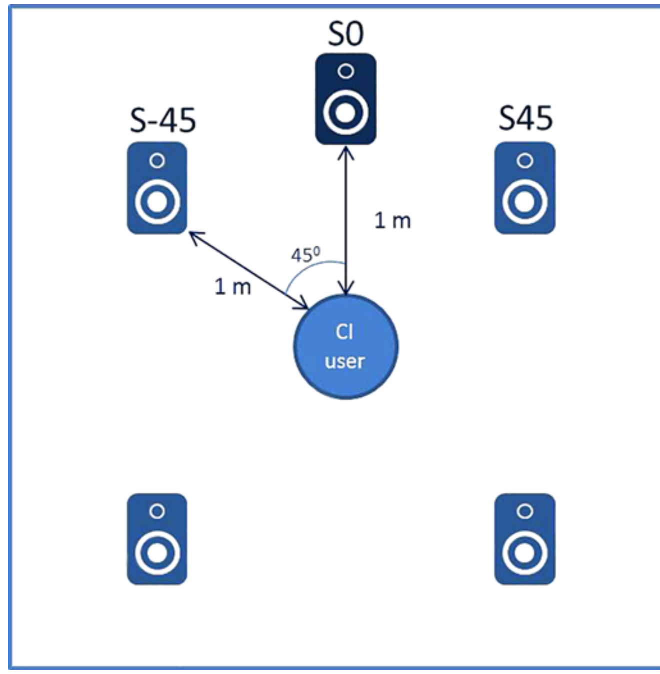

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Fig. 2. A schematic representation of the test environment. The cochlear implant (CI) user is in the middle of 5 loudspeakers, all at a distance of 1 m. The target signal is coming from S0 for the static listening condition and randomly from the loudspeaker at –45° or 45° for the dynamic listening condition.

the CI (ClearVoice, WindBlock, SoundRelax) and HA (NoiseBlock, SoundRelax, WindBlock) were turned off during the test sessions. Omnidirectional microphone modes were used for conditions 1–4.

Study Design and Procedures

This prospective study used a "within-subjects repeated-measures" design. Two factors were used: listening modality (CI only, bimodal, binaural beamformer), and speaker location (S0 or S-45/45). The study consisted of 1 visit in which speech-in-noise tests were performed for 6 different combinations of factors mentioned above: (1) CI only, S0, (2) CI only, S-45/45, (3) bimodal, S0, (4) bimodal, S-45/45, (5) binaural beamformer, S0, and (6) binaural beamformer, S-45/45) (Table 2). The order of the 6 conditions was randomized to prevent any order effects.

Test Environment and Materials

Dutch speech material developed at the VU Medical Centre [Versfeld et al., 2000] was used for testing speech recognition in noise. From this speech material, unrelated sentences were selected. A list of 20 sentences was presented at a fixed level of 70 dB SPL for each test condition. This level is representative for a raised voice [Pearsons et al., 1977] in background noise. The sentences were presented in a reception babble noise. We scored the correct words per sentence per list. An adaptive procedure was used to find the signal-to-noise ratio (SNR), targeting at a score of 50% correct words (speech reception threshold [SRT]). For each condition and

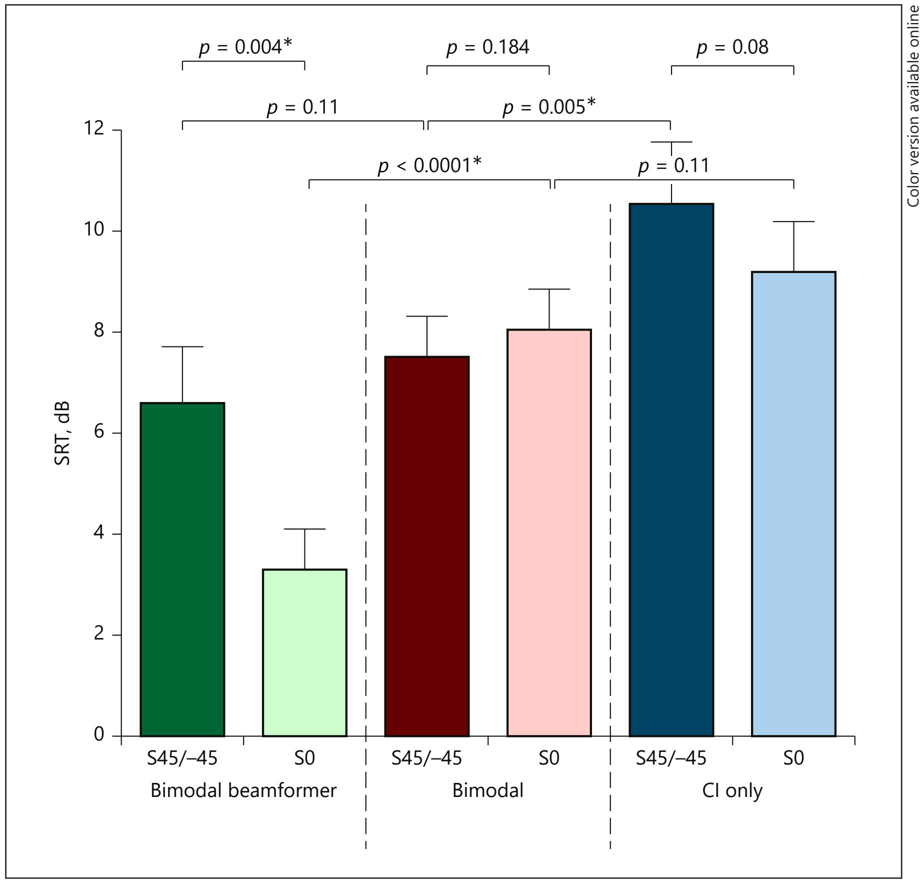

Fig. 3. The results of the speech perception in noise test for the 6 listening conditions. *p* values are corrected for multiple comparisons of the Wilcoxon signed-rank test. Asterisks denote significant differences. The error bars represent the standard errors of the mean. CI, cochlear implant; SRT, speech reception threshold.

each participant, a list with 20 sentences was randomly selected from a total of 25 lists. An extensive description of the speech reception in noise test is given in the paper by Dingemanse and Goedegebure [2015].

For the static condition, sentences were presented from a loudspeaker that was located at 1 m at 0° azimuth for conditions 1, 3, and 5. For the dynamic condition, sentences were presented randomly from a loudspeaker at –45° or 45° for conditions 2, 4, and 6, reflecting frequently occurring social situations in which a listener has to understand speech coming from >1 location. Four uncorrelated reception babble noises were presented with 4 loudspeakers located at –45°, 45°, –135°, and 135° azimuth. The rationale for this loudspeaker set-up was to simulate a diffuse, uncorrelated noise that exists in typical noisy daily life situations. Figure 2 displays a schematic of the test environment.

All testing was performed in a sound-attenuated booth. Participants were seated 1 m in front of a loudspeaker. For the speech-in-noise tests, research equipment was used consisting of a Roland UA-1010 soundcard and a fanless Amplicon PC.

Statistical Analysis

An a priori power analysis was performed with a required power of 0.8 and a significance criterion of 0.05, using the Wilcoxon singed-rank test with G*Power software.

For speech perception, we decided to choose a difference of ≥15% as clinically significant. With a slope of the psychometric function of 7.5%/dB on average, the difference between 2 test conditions must be ≥2 dB to be clinically significant. We planned paired comparisons between several test conditions. With a minimum of 2 dB between groups the effect size, d_z is 0.71. With these input parameters, the required number of participants is 15.

Data interpretation and analysis were performed with SPSS v23. Due to the low number of participants, nonparametric statistical methods were used. For the speech recognition in noise, the Friedman test was used to compare SRT over all listening conditions. Afterwards, post hoc comparisons with the Wilcoxon signed-rank test were performed. We used the Benjamini-Hochberg method to control the false discovery rate for multiple comparisons [Benjamini and Hochberg, 1995].

Results

The results for the speech recognition in noise test are presented in Figure 3. Significantly different SRT were found across the listening conditions (Friedman test: $\chi^2(5) = 42.9$, $p < 0.0001$). Post hoc comparisons using the Wilcoxon signed-rank test for the S0 condition showed no significant difference between the bimodal and the CI-

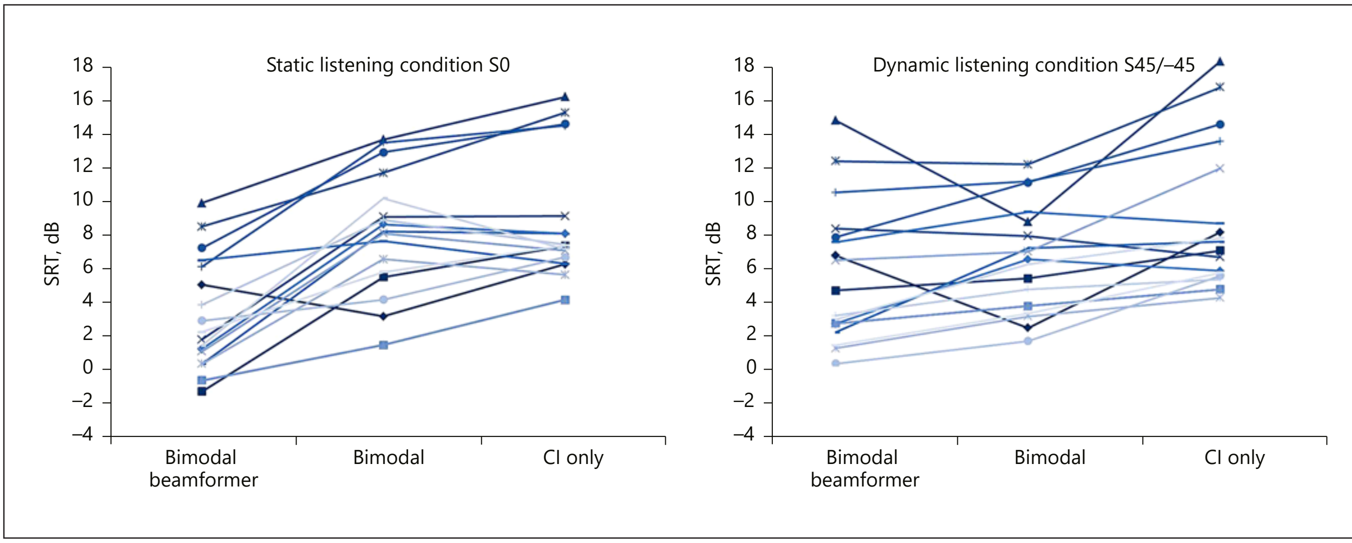

Fig. 4. The results of the speech perception in noise test for individual participants for the dynamic and static listening conditions. CI, cochlear implant; SRT, speech reception threshold.

only condition ($Z = -1.76$, $p = 0.11$), but a significant improvement was found for the binaural beamformer condition compared with the bimodal condition (4.7 dB, $Z = -3.55$, $p < 0.0001$). For the S45/-45 condition, a significant improvement of the SRT was found for the bimodal condition compared with the CI-only condition (3.1 dB, $Z = -3.11$, $p = 0.005$), while no significant difference was found between the bimodal condition and the binaural beamformer ($Z = -1.67$, $p = 0.11$). Comparing the results of the 2 different loudspeaker set-ups (S0 and S45/-45), the binaural beamformer provided a significantly better SRT for the frontal target speech than the dynamic speech condition (3.3 dB, $Z = -3.20$, $p = 0.004$). For the bimodal hearing and CI-only condition, no difference between the 2 loudspeaker conditions was found ($Z = -1.33$ [$p = 0.184$] and –1.98 [$p = 0.08$], respectively). Reported p values were corrected for multiple comparisons with the Benjamini-Hochberg method.

Figure 4 shows the SRT scores for the individual participants for the static and dynamic listening conditions. SRT scores varied largely among participants, from 0 to 20 dB; however, almost all participants showed the same pattern between the listening conditions. Only a few participants did not show a benefit for the binaural beamformer condition, and in 2 participants, the binaural beamformer deteriorated the SRT for the dynamic and/or static condition.

Discussion

This study showed a statistically significant and clinically relevant benefit of a binaural directional beamforming algorithm for bimodal CI users in term of better SRT for the frontal speech target signal. This is in agreement with our hypothesis. Speech was within the spot of the beamformer, and the noise sources, coming from other directions, were attenuated. Our results are comparable with the HA-only studies investigating the effect of binaural beamformers, where improvements in SNR were also found, together with large variability between participants [Best et al., 2015; Kidd et al., 2015; Neher et al., 2017; Picou et al., 2014].

Our results suggest that directionality reduces the localization performance of the participants, as no improvement was found in a more dynamic listening condition which is a more demanding task in terms of sound localization. Most probably, the listeners could not localize the sound source optimally, as their face was not turned towards it, leaving the target source outside the spot of the beamformer. These results are comparable with the study of Best et al. [2015], who also found reduced SNR for dynamic speech targets. In Picou et al. [2014], a deterioration in localization ability was found.

The bimodal hearing test condition was tested with the omnidirectional microphone mode to maximize the localization ability for the dynamic speech target. However, it is possible that with a conventional directional microphone mode in the CI and the HA, separately, a better SNR would have been found, especially for the frontal target signal. Future research with comparisons of different directional microphone algorithms is needed to provide more data as to in which situations which algorithm provides the largest benefit for bimodal CI users.

We chose to evaluate the effect of this binaural beamformer with the settings of the HA according to the clinical recommendations of the manufacturer, in order to be able to mimic daily clinical practice as much as possible. One of these recommendations is the use of the specially developed bimodal fitting rule, which we used in this study. However, although all different subparts of this fitting rule are based on scientific research [Ching et al., 2001; Neuman and Svirsky, 2013; Sheffield and Gifford, 2014; Veugen et al., 2016; Zhang et al., 2014], the effect on auditory functioning of the bimodal fitting formula as a whole has not been tested before. We found a relatively small effect of bimodal hearing compared to in the CI-only condition. A possible explanation could be that this is not the optimal fitting formula for all participants. Further investigations into this specially developed HA fitting formula and its effect on bimodal hearing are needed. Another limitation of the study is that we only tested the effect of the binaural beamformer in experimental conditions. Future studies should also contain field studies to evaluate if the found effect of the beamformer is consistent with the experiences of participants in their normal daily life.

Conclusion

The use of a binaural beamformer for bimodal CI users significantly improves the SNR for frontal target speech. Therefore, application of this binaural beamformer for bimodal users is an effective way to deal with challenging listening conditions, as it optimally uses hearing capacities while enhancing the SNR. However, counseling CI users about the function of this binaural beamformer is very important, as they need to know where the target signal is coming from to be able to obtain the optimal benefit.

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Disclosure Statement

The authors declare there were no conflicts of interest.

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