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Technical Report

Wireless and acoustic hearing with bone-anchored hearing devices

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Abstract

Objective: The efficacy of wireless connectivity in bone-anchored hearing was studied by comparing the wireless and acoustic performance of the Ponto Plus sound processor from Oticon Medical relative to the acoustic performance of its predecessor, the Ponto Pro. Study sample: Nineteen subjects with more than two years’ experience with a bone-anchored hearing device were included. Thirteen subjects were fitted unilaterally and six bilaterally. Design: Subjects served as their own control. First, subjects were tested with the Ponto Pro processor. After a four-week acclimatization period performance the Ponto Plus processor was measured. In the laboratory wireless and acoustic input levels were made equal. In daily life equal settings of wireless and acoustic input were used when watching TV, however when using the telephone the acoustic input was reduced by 9 dB relative to the wireless input. Results: Speech scores for microphone with Ponto Pro and for both input modes of the Ponto Plus processor were essentially equal when equal input levels of wireless and microphone inputs were used. Only the TV-condition showed a statistically significant (p < 0.05) lower speech reception threshold for wireless relative to microphone input. In real life, evaluation of speech quality, speech intelligibility in quiet and noise, and annoyance by ambient noise, when using landline phone, mobile telephone, and watching TV showed a clear preference (p < 0.01) for the Ponto Plus system with streamer over the microphone input. Due to the small number of respondents with landline phone (N = 7) the result for noise annoyance was only significant at the 5% level. Conclusion: Equal input levels for acoustic and wireless inputs results in equal speech scores, showing a (near) equivalence for acoustic and wireless sound transmission with Ponto Pro and Ponto Plus. The default 9-dB difference between microphone and wireless input when using the telephone results in a substantial wireless benefit when using the telephone. The preference of wirelessly transmitted audio when watching TV can be attributed to the relatively poor sound quality of backward facing loudspeakers in flat screen TVs. The ratio of wireless and acoustic input can be easily set to the user’s preference with the streamer’s volume control.

Key Words: Bone-anchored hearing; bone conduction device; conductive hearing loss; blue tooth; wireless connectivity

Introduction

In the rehabilitation of conductive or mixed hearing loss a bone conduction device (BCD) is a well-known and nowadays widely accepted option. In essence, the BCD consists of an external sound processor coupled to a percutaneous abutment on a titanium bone-anchored fixture.

The introduction of digital technology in bone conduction devices has substantially improved hearing performance over their analogue counterparts by virtue of reduced distortion and including adaptive directionality, dynamic feedback suppression, and more accurate software-based fittings using BC in situ thresholds (Bosman et al, 2011; DeSmet et al, 2013). However, users of these devices still encounter problems when communicating in everyday situations and there is an unmet need of many users for direct reception of streaming audio and direct connections to mobile phones and/or landline phones, television, and remote microphones.

In general, the number of listening environments in which the hearing aid user is satisfied with the performance of their hearing device has a strong impact on device utility (Kochkin, 2005). Therefore, it is highly relevant to increase performance in as many listening environments as possible. Telephone use is among the environments in which listeners are least satisfied, thus needing special attention. Difficulty understanding speech over the telephone is due to the absence of visual cues, to difficulties associated with coupling of the telephone to the hearing device, and background noise (Picou & Ricketts, 2011). Acoustic coupling of the telephone is often complicated by feedback when the telephone...
NFMI is a low power technology operating at 3.84 MHz, using wireless connectivity with a body-worn NFMI streamer as relay. Bilaterally fitted with occluding domes, this fitting strongly depends on the situation for listeners with presbycusis with its component of the hearing loss, the so-called ‘air-bone gap’. So, in bilateral conductive or mixed loss there is some freedom for optimally combining wireless and acoustic input signals. This contrasts strongly to the situation for listeners with presbycusis with its predominantly high-frequency hearing loss and its relatively favourable low-frequency hearing. These listeners often require large-vented ear moulds or even open fittings to reduce occlusion effects and for perceiving natural, low-frequency sound. But in these fittings a delicate balance has to be maintained between amplified high-frequency sound and unamplified low-frequency sound, leaving less room for manipulating wireless inputs relative to direct sound input to the ear canal. This is illustrated by Picou and Ricketts (2011, 2013) showing that in telephone listening the benefit of wireless signal routing relative to the microphone condition was only evident in hearing aid wearers that were strongly to the situation for listeners with presbycusis with its component of the hearing loss, the so-called ‘air-bone gap’.

The efficacy of wireless connectivity may be different with bone conduction devices than with conventional hearing aids, as in conductive (and mixed) hearing loss the contribution of direct, unamplified incoming sound is reduced by the conductive component of the hearing loss, the so-called ‘air-bone gap’. So, in bilateral conductive or mixed loss there is some freedom for optimally combining wireless and acoustic input signals. This contrasts strongly to the situation for listeners with presbycusis with its predominantly high-frequency hearing loss and its relatively favourable low-frequency hearing. These listeners often require large-vented ear moulds or even open fittings to reduce occlusion effects and for perceiving natural, low-frequency sound. But in these fittings a delicate balance has to be maintained between amplified high-frequency sound and unamplified low-frequency sound, leaving less room for manipulating wireless inputs relative to direct sound input to the ear canal. This is illustrated by Picou and Ricketts (2011, 2013) showing that in telephone listening the benefit of wireless signal routing relative to the microphone condition was only evident in hearing aid wearers that were bilaterally fitted with occluding domes.

A key feature of the Ponto Plus BCD sound processor is its wireless connectivity with a body-worn NFMI streamer as relay. NFMI is a low power technology operating at 3.84 MHz, using magnetic induction. Radiation is limited to the near field (≤1 m) and hence does not interfere with other wireless systems or other users. The streamer (1) serves as a remote control, and (2) it enables wireless connections to a mobile phone, to a landline phone using a ConnectLine Phone transmitter, to radio and TV using a ConnectLine TV transmitter, to an external microphone (ConnectLine Mic), and to other blue-tooth based audio devices. The Ponto Pro does not have wireless capabilities.

This study focuses on assessing the possible benefits of wireless connectivity by comparing the performance of Ponto Plus relative to an earlier released sound processor, the Ponto Pro. The efficacy of wireless connectivity was evaluated with speech-in-noise measurements using carefully equated output levels for microphone and streamer input. Ideally, with this setting both input modalities should provide equivalent intelligibility. Both wireless performance with Ponto Plus and microphone performance in Ponto Plus and Ponto Pro was measured in 19 individuals with more than two years’ experience in using BCDs. Patients were given a four to six-week trial period to acclimatize to the Ponto Plus device.

The study was conducted in accordance with the ethical guidelines for human experimentation as promulgated by Radboud University Medical Center, Nijmegen, Netherlands.

At the end of the study seventeen subjects decided to keep the Ponto Plus with the streamer. Only until all evaluations at the second visit were completed were subjects told that they could keep the device.

Materials and Methods

Subjects

Twenty native Dutch-speaking patients were selected to evaluate the Ponto Plus sound processor and its predecessor the Ponto Pro, with respect to speech communication and wireless connectivity (Ponto Plus only).

Patient selection criteria included conductive or mixed hearing loss, extensive BCD experiences, and (most) bone conduction thresholds within the 35-dB fitting range for a standard BAHD device (Snik et al, 2005). One patient was excluded from the study when audiometry showed bone conduction thresholds well outside the 35-dB fitting range.

The 19 patients were aged between 26 and 73 years (average: 46.1 years). They all had a bilateral conductive or mixed hearing loss. In four patients the hearing loss was due to chronic suppurative otitis media, in eight patients to a radical mastoidectomy after cholesteotoma removal, and in seven patients to bilateral congenital atresia. Thirteen patients were fitted monaurally and six patients bilaterally. Bilaterally-fitted patients were tested in the clinic with one device on their preferred side. They all used the two devices in daily life with wireless streaming to both devices.

Air and (unmasked) bone conduction thresholds were measured with standard audiometric procedures (ISO 389) and audiometers (Interacoustics Equinox with TDH-39P supra-aural headphones and B-71 bone conductor). Figure 1 shows the 25th, 50th, and 75th percentiles of the distribution of air and bone conduction thresholds to illustrate interindividual variation.

Frequency characteristics of Ponto Pro and Ponto plus

Gain and output of both Ponto Pro and Ponto Plus were measured with a TU-1000 skull simulator (Håkansson & Carlsson, 1989) using International Collegium of Rehabilitative Audiology (ICRA) noise (two person babble, one male, one female; file: 2pb1m1f). This measurement showed that Ponto Plus provides about 4.5 dB more output above 2 kHz than Ponto Pro at input levels of 47, 62, and 77 dB SPL (Bosman et al, 2014).

Calibration of microphone and wireless inputs

Ponto Plus features wireless connectivity through a body-worn streamer. By default, when streaming the telephone signal the acoustic (microphone) input is attenuated with 9 dB, the acoustic

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**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BAHD</td>
<td>Bone-anchored hearing device</td>
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<td>BC in situ</td>
<td>Bone conduction threshold measured with a BAHD</td>
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<tr>
<td>BCD</td>
<td>Bone conduction device</td>
</tr>
<tr>
<td>LTASS</td>
<td>Long-time average speech spectrum</td>
</tr>
<tr>
<td>NFMI</td>
<td>Near-field magnetic induction</td>
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<td>SRT</td>
<td>Speech reception threshold</td>
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receiver closely approaches the hearing device, despite the use of feedback cancellation algorithms (Latzel et al, 2001).

Listening difficulties with peripheral devices like telephone, radio, and TV may be reduced by connecting the output of these devices directly to the listener’s hearing device using wireless technology. Historically, wireless capability started with capturing the output of a telephone receiver with a telecoil in the hearing device. The efficacy of the telecoil, however, is critically dependent on the alignment of the telecoil with the magnetic field and the distance between source and hearing device (Sandrock & Schum, 2007). Nowadays, technologies like ‘Bluetooth Smart’ and intermediate (body-worn) NFMI relays are available for direct signal transfer to the hearing device (Yanz & Preves, 2007).

The efficacy of wireless connectivity may be different with bone conduction devices than with conventional hearing aids, as in conductive (and mixed) hearing loss the contribution of direct, unamplified incoming sound is reduced by the conductive component of the hearing loss, the so-called ‘air-bone gap’. So, in bilateral conductive or mixed loss there is some freedom for optimally combining wireless and acoustic input signals. This contrasts strongly to the situation for listeners with presbycusis with its predominantly high-frequency hearing loss and its relatively favourable low-frequency hearing. These listeners often require large-vented ear moulds or even open fittings to reduce occlusion effects and for perceiving natural, low-frequency sound. But in these fittings a delicate balance has to be maintained between amplified high-frequency sound and unamplified low-frequency sound, leaving less room for manipulating wireless inputs relative to direct sound input to the ear canal. This is illustrated by Picou and Ricketts (2011, 2013) showing that in telephone listening the benefit of wireless signal routing relative to the microphone condition was only evident in hearing aid wearers that were bilaterally fitted with occluding domes.

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At the end of the study seventeen subjects decided to keep the Ponto Plus with the streamer. Only until all evaluations at the second visit were completed were subjects told that they could keep the device.
input is not changed when streaming the TV’s audio signal. These default ratios can be individually set in the fitting software. In practice, users can override these settings by reducing the acoustic input with the volume control on the streamer.

To provide a straightforward comparison of microphone and wireless signals the output levels of both input modalities were made equal for both landline telephone and TV conditions, with the setup shown in Figure 2. All acoustic levels were calibrated with a B&K 2240 sound level meter.

For the acoustic telephone application the outputs of Ponto Pro and Ponto Plus were measured with the receiver of a landline telephone close to the microphone of the Ponto sound processor. A 3-mm felt cloth was used to dampen reflections from the metal surface of the TU-1000 skull simulator. The test material consisted of a broadband version of the nine digits used in telephone listening tests (Smits et al., 2004). The digits were played back from a PC with an RME Multiface II D/A converter, amplified and presented by a loudspeaker in a sound insulated box (Interacoustics TBS-25 hearing instrument test box) to a Siemens DECT Gigaset E49H telephone. The acoustic level at the microphone of the DECT telephone was set to 65 dBA. The telephone signal was transferred over landline to a Humantechnik Flashtel Comfort landline telephone with built-in audio amplifier. The telephone receiver was fitted in a plastic frame with four distance holders for exact positioning of the telephone receiver to the Ponto Plus. The distance holders provide a stable 2-cm distance between receiver and Ponto Pro or Ponto Plus. The acoustic output of the telephone receiver was presented at 2 cm to the microphones of a Ponto Plus in a second TBS-25 test box.

For both input modalities the output of the Ponto Plus was measured on a TU-1000 skull simulator (Håkansson & Carlsson, 1989). The TU-1000 output was digitized with an RME FireFace UCX A/D convertor for off-line analysis. A-weighted levels and third-octave output spectra were calculated with digital filters generated by MatLab (version R2011b; www.mathworks.com). The A-weighted output levels of the acoustic landline phone and Connectline Phone/Streamer setup were made equal within 1 dB.

For the TV-application the speech stimuli were delivered by a loudspeaker at 1-m distance at 0° azimuth and the noise by two loudspeakers at −45° and +45°. Output levels for microphone and wireless input were equated with Plomp and Mimpen (1979) sentences as stimulus. In the microphone condition the sentences were played back with a RME Multiface II D/A converter, amplified, and sent to a loudspeaker positioned at 1 m and 0° azimuth from the Ponto Plus. In the wireless condition the output of

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**Figure 1.** Left and right pure-tone thresholds of the 19 subjects for bone conduction (filled symbols) and air conduction (open symbols), expressed in 25-, 50-, and 75-percentiles and shown with downward pointing triangles, circles and upward pointing triangles, respectively.

**Figure 2.** Setup for calibrating the acoustic and streamer telephone condition. (1, 2): PC and RME MultiFace II D/A convertor. (3): Ecler MPA4-80R power amplifier. (4, 5): TBS-25 hearing aid test box (Interacoustics) with built-in loudspeaker and Siemens Dect Gigaset E49H telephone. (6): ConnectLine Phone transmitter connected to the landline of the Dect telephone and linked to a streamer. (7, 8): Human Technik Flashtel Comfort landline telephone receiver and Ponto Pro or Ponto Plus sound processor with TU-1000 skull simulator in a TBS-25. (9, 10): PC and RME FireFace UCX A/D convertor.

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1www.oticonmedical.com/Medical/OurProducts/Individualized%20Fitting/Genie%20Medical%20software.aspx
the D/A convertor was directly coupled to a ConnectLine TV transmitter linked to the Ponto Plus by a streamer. Levels of the noise masker were made equal to the stimulus level. The A-weighted output levels measured with a TU-1000 were made equal within 1 dB for the microphone (loudspeaker/microphone) and the wireless (ConnectLine TV/streamer) condition.

**Measurements**

The objective evaluation involved measuring speech perception in noise with Plomp and Mimpen (1979) material and procedures. The sentence material consists of everyday Dutch sentences of eight or nine syllables, presented against a background of filtered white noise with the same long-term average spectrum of the speaker (LTASS noise). Speech was presented frontally at 0° azimuth and the masking noise either at 0° or 90° azimuth (S0N0 or S0N90 condition) at the ipsilateral, implanted side with a level 65 dBA. Both Ponto Pro and Ponto Plus were tested in omni-directional condition) at the ipsilateral, implanted side with a level 65 dBA. Both Ponto Pro and Ponto Plus were tested in omni-directional mode and in ‘full-focus’ directional mode.

The TV-setup was also measured with Plomp and Mimpen sentences, but with the 65-dBA LTASS masking noise presented at −45° and +45° azimuth. In microphone condition speech was presented at 0° azimuth, and in the streamer condition by the streamer.

The intelligibility of landline telephone conversations was evaluated with the original full-bandwidth version of the numbers and noise taken from the digits-in-noise test (Smits et al, 2004, 2013). This test material consists of the numbers 0–9 presented in triplets against LTASS noise of the same speaker. Uncorrelated LTASS masking noise was presented by two loudspeakers positioned at 1 m and at −45° and +45° azimuth. For the microphone input condition the digits were presented frontally at 0° azimuth. For streamer input the digits were sent to a ConnectLine TV box coupled to a Ponto Plus fitted with a streamer.

Subjective evaluations were carried out with a proprietary questionnaire, rating speech intelligibility, sound quality, and noise annoyance.

**Results**

Sentence perception in noise was not significantly different (p > 5%) for Ponto Pro and Ponto Plus both in the S0N0 condition in omni-directional mode, and in the S0N90 condition in omni-directional and in directional mode. With either device in omni-directional mode an SRT of −3.7 dB signal-to-noise ratio was found in the S0N0 condition. The SRT increased by 1.3 dB when moving the noise source from 0° to 90° azimuth. For both devices with full-focus directionality, the SRT in the S0N90 condition improved (was lowered) by 1.8 dB to −4.1 dB, close to the value for the S0N0 condition (Bosman et al, 2104).

A schematic of the measurement setup for the landline telephone and the TV condition is shown in Figure 3. Figure 3 (a) shows that in the omni-directional microphone mode the SRT for the digits-in-noise (Smits et al, 2004) is −1.6 dB and −1.7 dB for Ponto Pro and Ponto Plus, respectively. The SRT for Ponto Plus in streamer mode was −2.3 dB. None of these differences were statistically significant (paired comparisons Student’s t-test, p > 5%). So, streamer input is essentially equivalent to the microphone input of a telephone receiver positioned at a distance of 2 cm from the sound processor.

Sentence perception for the TV condition was measured with Plomp and Mimpen (1979) sentences presented at 0° azimuth and independent LTASS noise at −45° and +45°. Figure 3 (b) shows that for the microphone input mode of Ponto Plus and Ponto Pro differences were not significant (p > 5%). However, the TV-box and streamer combination provided a small but significant (p < 5%) advantage of 1.4 dB over the microphone input with either device.

Figure 4 shows the results on proprietary questionnaires using visual-analogue scales, with anchors of very poor = 0 and very well = 10, probing speech quality, speech intelligibility in quiet and noise, and for annoyance by ambient noise, with anchors of no annoyance = 0 to extreme annoyance = 10 when using the telephone and watching TV. Seven subjects completed the questionnaire for landline phone, nine subjects for mobile phone and 15 subjects for watching TV. Figure 4 (a, b, and c) show a

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**Figure 3.** Results for (a) the landline telephone with the digits-in-noise test (Smits, 2004) and (b) for the TV-condition with the sentence-in-noise test (Plomp & Mimpen, 1979) for Ponto Pro, Ponto Plus, and Ponto Plus with streamer. The differences in the telephone condition (a) are statistically not significant (p > 0.05). In the TV-condition (b), the SRT with streamer is 1.6 dB and 1.1 dB (p < 0.05) lower (more favourable) than for Ponto Pro and Ponto Plus, respectively.
strong positive effect ($p<0.01$) of streamer input versus microphone input both for landline and mobile phone and for watching TV. Due to a smaller number of respondents the annoyance by ambient noise with the landline phone is only significant at $p<0.05$.

Figure 4 (c) corroborates our informal findings with a TV demo setup in the clinic running news items. We saw almost instantaneous acceptance of the streamer signal when connecting it to a Ponto Plus, with subjects spontaneously mentioning better speech understanding and reduced listening effort.

**Discussion**

Score differences with carefully matched levels of microphone input for Ponto Pro and microphone and streamer input for Ponto Plus appeared small and in most conditions insignificant. However, the subjective evaluation of speech quality, speech intelligibility in quiet and noise, and annoyance by ambient noise, when using the telephone and for watching TV showed a clear preference for the Ponto Plus system with streamer.

The equivalence of microphone and streamer mode with equated output levels should not be underestimated for practical applications, as this finding essentially corroborates the viability of a NFMI streamer for high-quality signal transfer. Wireless signal transfer implies, for the telephone application, a release from the burden of carefully positioning the telephone receiver closely to the sound processor without running into feedback issues.

A second advantage of a streamer is that under unfavourable listening conditions it can provide an inherently much better signal-
to-noise ratio than with the microphone input. This is especially true for (mobile) telephone, TV, and other applications where the source signal can be directly transmitted to the hearing device. In conductive and mixed hearing loss the role of direct incoming, unamplified sound into the ear canal is relatively small, as direct sound is attenuated by the conductive component of the loss. This provides some freedom for optimally combining inputs from various sources, thus making this an ideal target group to benefit from wireless signal routing. For example, for this target group reduction of the microphone input when using the telephone is very effective in reducing ambient noise and thus improving telephone conversations.

The preference of wirelessly transmitted audio when using the telephone can be directly attributed to the 9-dB reduction of the microphone signal. The wireless preference when watching TV is most likely due to the relatively poor sound quality of backward facing loudspeakers in modern flat screen TVs and in combination with deteriorating effects of room acoustics.

The ratio of streamer versus microphone input may be easily set to the listeners’ preference. For example, the ASHA (2002) guideline for FM systems requiring a 10-dB higher output for streamer output relative to an equivalent microphone input may thus be easily realized without running into feedback issues. The output levels for microphone and streamer inputs and the spectral balance for streamer input can be individually set for different streaming inputs with the Genie Medical fitting software.

In conclusion, this study shows equivalent speech intelligibility with streamer and microphone inputs at equal input levels. Wireless communication provides a significant benefit when communicating over the phone due to a 9-dB reduction of ambient sounds. The subjective preference of wirelessly transmitted audio when watching TV can be attributed to the relatively poor sound quality with flat screen TVs and to poor room acoustics.

Acknowledgements

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Declaration of interest: The authors declare no conflicts of interest.

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