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Bone Conductors, Signals and Sores

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ABSTRACT

Anecdotal reports associate long-term use of a headband bone-conductor with the potential formation of skin pressure sores. When a bone conductor applies skin pressure that exceeds blood capillary pressure, capillaries collapse and blood flow ceases. Pressure-sores can develop if blood flow is cut-off for extended periods of time. To test if bone conductor users were at risk of developing sores, eleven adults were fitted with headband-worn bone conductors (BC461 and B71). The skin contact-pressure was measured to see if it exceeded 3.7 kPa, the estimated pressure needed to collapse capilaries at the mastoid process. Contact pressure was found to be substantially greater than capillary pressure (17 kPa for a standard adult headband and B71, 11 kPa for a BC461). Pressure can be reduced by increasing contact area so a BC461 bone conductor was modified to attach larger footplates. The measured pressure for a 38 mm footplate diameter was found to produce a contact pressure close to the capillery closure pressure. However, increasing the contact area changes the device mechanical-coupling impedance and sensitivity. Threshold measurements for the larger footplate device showed slightly poorer results. Preliminary measurements indicated decreased skin sensitivity to vibration with larger footplates. To conclude, small footplate bone conductors (e.g., BC461) should be fitted with the least pressure possible commensurate with a bone conductor staying on the head. The skin contact position for the bone conductor should be moved regularly to avoid prolonged disruption of capillary blood supply to the skin. For future devices, it is recommended that bone conductors are designed with larger footplate areas. This reduces skin contact pressure with a small loss in measured thresholds, reduced skin vibration sensitivity and improved wearer comfort.

INTRODUCTION

Motivation

The motivation for this work developed from the anecdotal reports of audiologists. It has been known that headband-worn bone conductors are capable of creating pressures sores at the point of contact with the skin. Dealey (2005) defines a pressure sore as (when the)

> Soft tissue of the body is compressed between a bony prominence and a hard surface causing pressure greater than capillary (closing) pressure, localised ischemia occurs.

Aims

The first aim of this paper is to discuss the mechanism for the formation of pressure sores that may occur with the fitting of a headband worn bone conductor. This has been previously discussed in detail; Raicevich et. al., (2008).

One solution is to increase the bone conductor contact-area. However, this may change the device mechanical coupling impedance to the head. Therefore, a second aim is to measure any changes in signal transmission due to an increased footplate area.

A third aim is to measure user comfort with a larger footplate. A fourth aim is to offer a guideline for the contact pressure to use when fitting a bone conductor. A final aim is to make a recommendation for the size of footplates for a future bone-conductor design.

Background

The mechanism for skin ulceration due to bone conductor contact-pressure has been poorly understood in the field of audiology. The medical domain provides a body of knowledge describing how pressure sores may result. Houle (1969) reported that 'prolonged obstruction of local capillary circulation leads to death of the cell' (p. 587). Houle went on to describe this was more likely to occur where external pressure is applied to skin over areas with underlying bone close to the skin surface. The mastoid process is a good example of this physiology.

Capillary Critical Closure Pressure

A question is raised for capillary blood pressure. What level of external pressure will collapse the capillary blood vessel? Using Laplace's law of equilibrium, Burton (1951) was able to predict that when the outside pressure on the walls of a small blood vessel exceeded the interior blood pressure by a small value, the blood vessel would close.

Roddie and Shepherd (1957) later confirmed this prediction. They reported when an external pressure was applied across the capillary blood vessel walls and was increased to a pressure greater than the capillary pressure, the blood flow through the finger would quickly fall to zero, even though the perfusion pressure (the drop from mean arterial to venous pressure) was still as high as 4.7 to 8.0 kPa. The pressure at which capillaries would close was termed the 'Critical Closure Pressure'. Capillaries offer a connecting path between the arterial vessels (the higher-pressure side of the heart) with the venal or lower-pressure side of the heart.

An early study of capillery blood pressure was carried out by Landis (1930). Based on measurement of 19 subjects, reporting a mean capillary pressure of 2.7 kPa, ranging from 2.0–4.3 kPa. Landis demonstrated a useful relationship of blood pressure and the height of the measurement from the heart. Blood pressure was measured in the capillaries of the finger, with the height of the finger placed at the same height as the heart. The finger could be used as a convenient moveable point enabling measurement of blood pressure at different heights above the heart. He showed that this capillary pressure varied as a function of the finger height relative to the heart.

All that is needed is a way to establish capillary pressure at the mastoid process. Parazynski, et. al., (1991) reported blood capillary pressure of 3.7 kPa measured at the lips. Since the height of the mastoid process is at approximately the same height above the heart as the lips, then it would be reasonable to assume that capillary pressure at the mastoid process should also be 3.7 kPa. Based on the findings of Landis it would be reasonable to expect this figure may vary between individuals based on age, health, and the individual's height from the heart to the mastoid process. A more accurate value of capillary pressure at the mastoid process will require measurement.

Using the estimated capillary pressure at the mastoid process, a maximum permissible bone-conductor pressure can be recommended. To avoid collapsing the capillaries, the external pressure applied to the skin by the bone conductor should not exceed (approximately) 3.7 kPa.

Contact pressure can be measured using headband force and bone conductor area using the equation:

Pressure = Force / Area **(1)**

With:
Pressure in units of Pascals (Pa)
Force in units of Newtons, (N)
Area in units of m^2

To establish a baseline of results, the force applied by an adult head was measured for three different strengths of headbands: a stretched and weakened headband, a standard one and two headbands taped together for increased force.

In the past audiologists have stretched headbands to weaken them and reduce the bone conductor contact pressure.
The problem with this approach has been that a weaker headband also tends to slip more readily from the the head.

Reduced contact pressure can be achieved by increasing the footplate area. The largest footplate practical would be limited by either wearer comfort or the ability to fit the device on the measurement surface of an artificial mastoid. A modified BC461 bone conductor was arranged with a range of clip-on footplates of different diameters for testing.

The artificial mastoid presents a mechanical load impedance that emulates the impedance of a mastoid process. Altering the footplate area could change mechanical impedance and hence signal transmission through the skin and skull. To test this, device sensitivity was measured using an artificial mastoid. Bone conduction sensitivity was measured in N/V (Newtons of force per Volt of drive signal).

At lower frequencies, below around 250 Hz, the skin has tactile sensitivity to vibration. The sensitivity is due to mechano-receptors in the skin, for example, Pacinian Corpuscles as reported by Kandel et. al., (2000). A larger footplate may change the tactile response of the skin. To check skin sensitivity, low frequency measurements were made using a BC461 bone conductor with different footplate areas.

Bone conductor wearer comfort is important therefore, the comfort of a BC461 was tested using different size footplates.

METHOD

Bone conductor contact-pressure and sensitivity with normal footplate

Eleven adult subjects were tested to measure the force a bone-conductor applies to the head.

For this measurement an Oticon model BC461 bone conductor (BC461, 116Ω, 8.8mH @ 1 kHz, mechanicaly unloaded, 13Ω DC) was used with an adult size stainless-steel head band (Hal-Hen, model 207). A matching headband supplied with the B71 (used for audiological testing) was used for the B71 force measurements described in Table 1.

Headband force was calculated using the following relationship:

Force = Mass * Acceleration **(2)**

With:
Mass in units of Kg
Acceleration equals 9.8 m/s^2

Figure 1 shows a mass measuring scale used to measure the force applied to the head by a headband and bone conductor. The scale would pull against the headband and the mass would be read from the scale when the contact surface of the bone conductor just lifted from subject's head.

Source: (Raicevich)

Figure 1 shows measurement of headband force

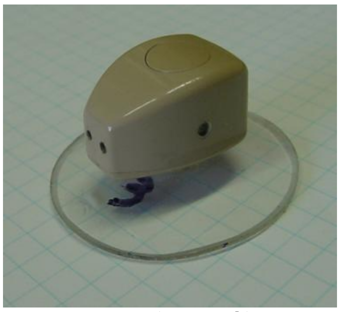
Figure 2 shows a BC461 placed on an artificial mastoid (BK4930) to measure device sensitivity. Sensitivity was measured as signal force for drive voltage in units of dB re 1 N/Vrms. A static force of 5.4 N was applied to the top of the bone conductor (ANSI S3.6, 2004), (not shown).

Source: (Raicevich)

Figure 2 BC461 on artificial mastoid for sensitivity measurement

Bone conductor contact-pressure and sensitivity with larger footplate

Figure 3 shows a BC461 modified to take five different (clip-on) footplate sizes. This arrangement measured the effect of reduced contact pressure on hearing thresholds and skin sensitivity to vibration. Two subjects were used for both these measurements.



Source: (Raicevich)

Figure 3 shows the modified BC461 with clip-on footplate

Each footplate was formed with a small curvature to attempt matching the shape of the artificial mastoid surface. This was done to improve the mechanical coupling of device to artificial mastoid. The smallest footplate emulated the area of the BC461 bone conductor. This allowed direct comparison of results for each clip-on footplate.

Figure 4 shows a BC461 with larger footplate as it sits on the measurement surface of an artificial mastoid. The artificial mastoid surface measured 40mm diameter. A footplate diameter of 38mm was chosen to avoid interfering with the edge of the measuring surface and to increase user comfort relative to a standard BC461.

Source: (Raicevich)

Figure 4 BC461 with large footplate on artificial mastoid for sensitivity measurement

Changes in skin sensitivity for different footplate areas

The skin on the wrist and the mastoid process were qualitatively judged to have similar tactile response. Threshold measurements for vibrations were made using the top of the wrist. The wrist provided a region of skin with less hair than the mastoid process. It would be reasonable to assume this would give worst-case sensitivity to vibration (less hair to insulate the skin from vibrations). A BC461 with different footplates was used to detect any measurable changes in skin sensitivity at 250 Hz.

Comfort for larger footplates

Comfort scores were made using two subjects. Comfort was quantified using a scale of 0 to 100, where zero represented “totally uncomfortable” and 100 represented “totally comfortable”. The comfort of each larger footplate was estimated by comparison to a standard BC461. Each device was fitted using an adult headband. The ratings were taken for different pad size and headband forces.

RESULTS

Measured contact pressure for standard bone conductors

The Oticon BC461 bone-conductor skin contact-area measured 343 mm^2. Radioear B71 bone-conductor skin contact-area measured 224 mm^2.

Table 1 shows the headband forces measured using the setup shown in Figure 1. The values are the average for 11 subjects. The three headband forces represent, a stretched adult headband (top row), a normal adult headband and two headbands taped together (bottom row). The contact pressure applied by the bone conductor to the head is measured in kPa.

Table 1 Headband force and Bone conductor contact pressure, normal footplate

Headband Force (N)	BC461 Oticon (kPa)	B71 Radioear (kPa)
2.5	7.3	11.2
3.8	11.1	17.0
5.4	15.7	24.1

Source: (Raicevich et. al., 2008)

The middle row results for Table 1 show a normal adult headband for a BC461, representing an audiological fitting and a B71 with an alternate headband, supplied for audiometric tests, representing clinical testing. Both grossly exceeded the estimated pressure needed to collapse capillary vessels at the mastoid process of 3.7 kPa.

Measured contact pressure for bone conductor with larger footplate

Three footplates were chosen to measure contact pressure and sensitivity. Pad 1 area was made similar to the BC461 footplate (346 and 343 mm^2 respectively).

Table 2 shows the headband forces for a mass of 0.125, 0.25 and 0.5 kg respectively. The combinations that equalled or were less than capillary closure pressure are marked in bold.

Table 2 Contact pressure (kPa) for different combinations of headband force and contact area

Pad number	Pad 1	Pad 3	Pad 5
Diameter (mm)	21	38	57
Area (mm^2)	346	1134	2552
Headband force (N)			
1.2	**3.5**	**1.1**	**0.5**
2.5	7.3	**2.2**	**1.0**
4.9	14.2	4.3	**1.9**

Measured bone conductor sensitivity in N/V

Figure 5 shows device output measured using an artificial mastoid (BK4930) and 5.4 N static force. Both Pad 1 and Pad 3 show a slight drop in force output above 400 Hz, relative to the BC461 result. The lack of change in frequency of the resonances at 400 Hz and 1.2 kHz suggest signal attenuation due to mechanical losses.

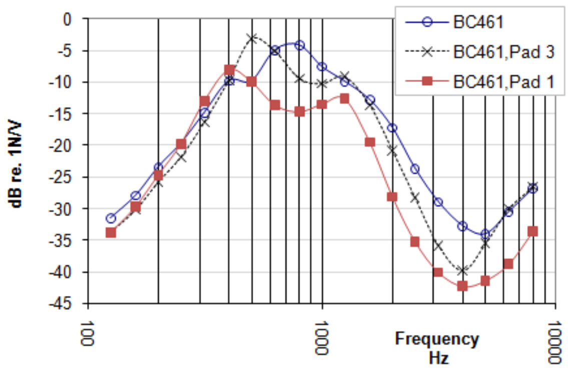


Figure 5 Force sensitivity in N/V dB re 1N/V, using different footplates

The graph shows that above 400 Hz, The larger Pad 3 gives more force per Volt (above 400 Hz) than the smaller Pad 1.

Measured bone conductor thresholds with changed static headband force

Figure 6 shows threshold measurements using Pad 1 and the same BC461 with contact pressures of: 3.7, 7.3 and 14.7 kPa.

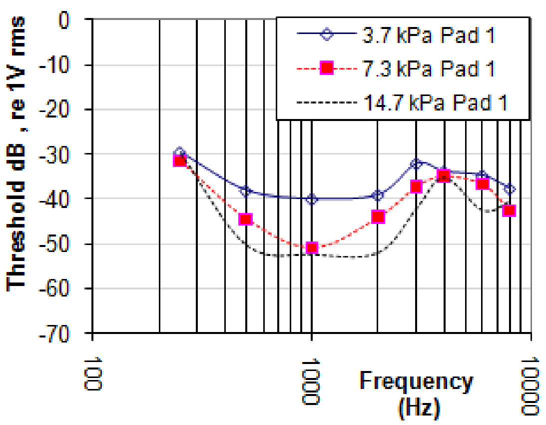


Figure 6 Normal hearer thresholds re 1Vrms, vs. contact pressure (kPa) using Pad 1 with BC461

Thresholds improved with higher contact pressure. Solid lines in the graph indicate static pressures lower than capillary closure. Conversely, dotted lines indicate the contact-pressure exceeded capillary collapse pressure. The threshold values on the vertical axis are shown in dB relative to 1Vrms drive signal. The horizontal axis shows frequency in Hz.

Graphs 5 and 6 are combined to report thresholds values in force, Newtons. Figure 5 reports -20 N/V dB re 1V at 250 Hz. Combining device sensitivity with figure 6, and a conduction threshold of -30dB at 250 Hz gives a force threshold of -50 dB re 1N (70 dB re 1μN).

Measured bone conductor thresholds with fixed static headband force and changed pad size

Figure 7 shows threshold measurements for a normal hearer, a BC461, three pad sizes and contact-pressures:

Pad 1 produced 14.7 kPa
Pad 3 produced 4.1 kPa
Pad 5 produced 1.9 kPa

This measurement shows pad size affects vibration thresholds. The largest (500 gm) headband force gave measurements that were more reliable.

For this graph, the dotted lines indicate contact pressure greater than capillary collapse pressure. Pad 3 produced a pressure marginally above capillary closure pressure.

A red cross represents skin sensitivity to vibration -10 dB (250 Hz), using Pad 3. The skin shows 18 dB poorer threshold sensitivity than the conduction threshold for a normal listener. Using Figures 5 and 7, the skin threshold to vibration is (-10 -22 + 120 dB) = 88 dB re 1μN at 250 Hz.

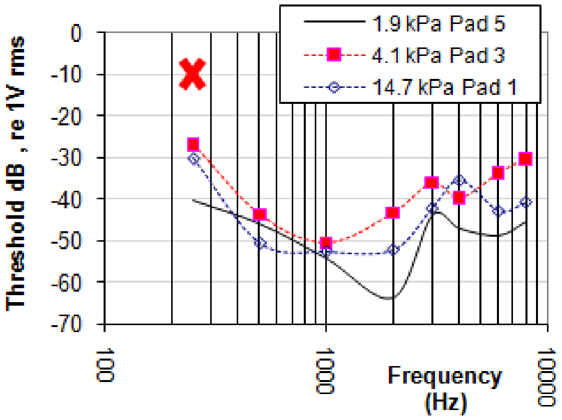


Figure 7 Normal hearer thresholds re 1 Vrms for three pad sizes Pad1 (14.7 kPa), Pad3 (4.1 kPa), Pad5 (1.9 kPa)

Skin vibration thresholds

Measurements were taken using pads placed on the back of the wrist. The measurements describe skin thresholds with respect to pad size and static force (at 250 Hz).

Figure 8 shows wrist-based skin sensitivity to vibration for five pad sizes with the static force on the BC461 varied from 1 to 5 N. The averaged results for pads 1 to 5 show a 2dB change in sensitivity with headband force ranging from 1 to 5 N. The averaged sensitivity increases with greater headband force.

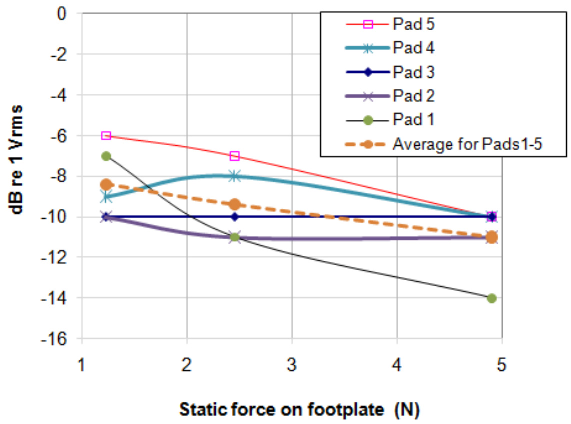


Figure 8 Skin sensitivity thresholds (for wrist) in dB re 1 Vrms using 4.9N static force.

Comfort with respect to footplate area and head-band force

Figure 9 shows comfort increased with increasing pad size. Pad 3 shows a very similar pressure to the capillary closure pressure, shown as a dotted line representing 3.7 kPa.

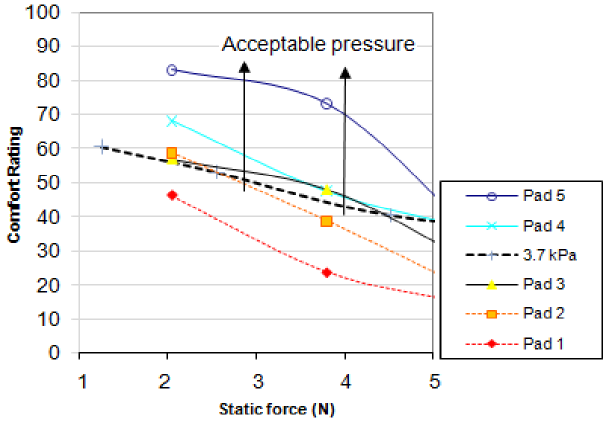


Figure 9 Comfort rating different pad size and band force

DISCUSSION

Table 1 shows the measured skin contact pressure for the normal adult headband with a standard BC461and B71 exceed the recommended contact pressure needed to collapse capillary blood vessels by 300% and 450% respectively.

Having established that the BC461 and B71 both exceeded capillary closure pressure, larger footplates were then explored. Table 2 showed Pad 3 static pressure ranged from 1 to 4.1 kPa for headband forces of 1.2 to 4.9N. This contact pressure largely avoids capillary closure. The largest footplate capable of accommodation on an artificial mastoid measurement surface was Pad 3.

The three headband forces (2.5, 3.8 and 5.4 N) were chosen to coincide with the static force specified in ANSI S3.6 (2004), 5.4 +/- 0.5 N for audiometric measurements and IEC60118.9 (1985), 2.5 +/-0.3 N for calibration of a hearing aid bone vibrator on an artificial mastoid. The 3.8 N headband force represents the mean adult headband force for 11 measurements. Note that both standards fail to indicate suitable levels of headband force for long-term use of bone conductors.

Device sensitivity and threshold results for larger clip-on footplates were compared with a clip-on footplate area the same as a BC461. This avoided confounding effects such as transducer to footplate changes in mechanical coupling impedance, for example, the method of attaching the footplate.

The largest footplate, Pad 5, could touch (interfere) with the rear of the Pinna. It was also too large to fit on the artificial mastoid for measurement.

Pad 3 provided the maximum permissible footplate size that could fit on the measurement surface of an artificial mastoid. It provided contact pressure close to or equal to capillary closure pressure at the mastoid process. The perceived comfort increased compared to Pad 1.

The bone conduction threshold can be compared using a pad pressure similar to capillary closure for Pads 1 and 3. Figures 5,6 and 7 show that Pad 1 provides 66 dB re 1μN while Pad 3 provides 60 dB re 1μN, at 1 kHz. The larger Pad 3 requires 6 dB re 1μN greater force to provide the same bone conduction threshold.

Normal Hearer Vibration to Skin threshold gap

Figures 5 and 6 describe Pad 3 with a bone conduction force threshold of 70 dB re 1μN at 250 Hz and skin threshold sensitivity to vibration of 88 dB re 1μN at 250 Hz. This means there is an 18 dB gap between vibration signal level threshold and skin sensitivity for a normal hearing subject.

The artificial mastoid was designed for measuring small contact area bone conductors such as the BC461 and B71.

Figure 5 showed changes in bone conductor sensitivity when using larger footplates. The change in sensitivity may be the result of changes in the mechanical coupling impedance between the device being measured and the artificial mastoid.

CONCLUSION

Pressure sores can form when capillary blood flow is stopped by excessive external pressure to the skin. This is particularly so if the skin is situated over a bony portion of the body such as the mastoid process.

The BC461 and B71 grossly exceed capillary closure pressure allowing the potential for pressure sores to develop if used for prolonged periods. A guideline for fitting these devices is to use no more headband force than necessary to keep the device on the head. Often reposition the bone conductor on the head, along with the opposite end-pad of the headband to avoid forming pressure sores.

A better solution is to increase bone conductor contact-area. Figure 7 showed little change in vibration thresholds when comparing the results for pad 1 and 3. The perceived wearer comfort increased with large footplates.

A bone conductor footplate of 38 mm diameter (pad 3) combined with a Hal-hen 207 adult headband provided a contact pressure that bordered on capillary closure pressure. A larger footplate was not possible if device vibration measurements were to be made using an artificial mastoid.

For future devices, it is recommended that bone conductors are designed with larger footplate areas. This reduced skin contact pressure, reduced skin vibration sensitivity and improved comfort. The downside is a small loss in vibration signal thresholds.

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