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HEARING PROTECTORS: NOISE ATTENUATION AND COMFORT

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Abstract

In many industrial and military situations it is not practical or economical to reduce the noise to levels that do not present either a hazard to hearing or annoyance. In these situations, personal hearing protection devices are capable of reducing the noise by up to around 40 dB. Although the use of a hearing protector is recommended as a temporary solution until action is taken to control the noise, in practice, it ends up as a permanent solution in most cases. Therefore, hearing protectors must be both efficient in noise attenuation and comfortable to wear. Comfort in this case is related to the acceptance of the user to wear the hearing protector consistently and correctly at all times. The purpose of this paper is to review publications related to earmuff comfort, most of which are based on measurement of the total headband force and subjective evaluation using questionnaires. Most of the published results show a weak correlation between total headband force and subjective evaluation. This paper presents new quantitative indices based on the comfort parameters, mainly measurements of the contact pressure distribution between the earmuff cushions and circumaural flesh of the human head. The comfort parameters were investigated and equations developed to calculate comfort indices and overall quality indices. The calculated indices are correlated with subjective evaluations. Measurement results for the pressure distribution of ten earmuffs show good correlation with subjective evaluation.

Keywords: Hearing Protector Comfort.

1 Introduction: Earmuff comfort

When noise control at the source is not economically feasible in the short or medium term, hearing protectors are the only solution. Therefore, hearing protectors are the salvation of workers in noisy environment and should be given maximum attention for research and development to advance the technology required for high quality protectors which satisfy the noise protection requirements of the users and also the legislation. Hearing protectors should be used for 100% of the work shift, otherwise very little noise attenuation is gained, and they should be accepted by the users, so that they will be used consistently and correctly the whole time. This means that the hearing protector should be COMFORTABLE. All literature published on comfort, to our knowledge, has been based on the total force of the headband, or the average pressure (dividing total force by contact area) and evaluation based on the reaction of a group of jurors who subjectively evaluate the comfort. However, a large number of the studies published on earmuffs show that there is often a lack of correlation between comfort and headband total force or average pressure. Some published results, as shown later in this literature review, even show the contrary situation, that is, a strong headband force is more comfortable than a weak headband force.

Although comfort may appear to be a secondary requirement at first glance, it must be realized that an uncomfortable hearing protector device (HPD) becomes intolerable after prolonged wear and is typically removed or refitted for comfort, and not for best attenuation, leaving gaps for noise leakage.

Pressure exerted by an HPD on the skin and underlying tissue and bone is probably one of the most common direct causes of discomfort. If the pressure is strong and continues for a relatively long period of time, the pain may become intolerable. Two factors are involved in this regard, the total force of the hearing protector against the skin and the distribution of the pressure.

The pressure exerted by earmuffs varies proportionally with the force applied by their means of support. When the total force is well distributed over a large area, the resulting pressure is lower than when it is concentrated at a few contact points.

In order to ensure a large area of contact with the skin, earmuffs should not only be of a size and shape compatible with the ear and head anatomy, but they should also be made of a compliant material. When the area of contact between the hearing protector and the skin is large, the total force acting on the flesh lining must be limited to a value that permits proper circulation of the blood [Warwick, 2007]. A certain amount of pressure on the skin is necessary to hold the hearing protector in place and to provide sound attenuation. As the pressure diminishes, the impedance of the skin decreases and the vibration of the hearing protector as a rigid body increases. With too little pressure, noise leaks may be created. Therefore, it is difficult to specify the maximum acceptable pressure.

The purpose of this paper is to review the publications on earmuff comfort, most of which are related to measuring headband total force and subjective evaluation. This paper presents quantitative indices based on the comfort parameters, mainly the measurement of the contact pressure and force distribution between the earmuff cushions and the circumaural flesh of the human head. This requires the development of a measurement system using a new technique involving an array of pressure sensors to measure the pressure distribution along the contact area. This new technique is reviewed and measurements are carried out for ten hearing protectors mounted on two flat parallel surfaces, mounted on an artificial (or dummy) normalized head (ANSI S3.36-1985) and mounted on a real human head. The comfort parameters were investigated and equations developed to calculate the comfort and overall indices. By measurement of the contact pressure, it is possible to calculate the following parameters which are directly related to comfort (as shown later), in addition to the weight of the hearing protector

1- Force and pressure distribution values.
2- Center of gravity of the pressure distribution.
3- Contact area in relation to total cushion area.
4- Total force of the headband.
5- Weight of the hearing protector.

Other parameters, such as those listed below, can be added to cover most of the overall quality of an earmuff.

1. Noise attenuation.
2. Temperature and humidity distribution between the earmuff cushions and circumaural flesh of the human head.
3. Cost of the hearing protector.

Many other factors can also be considered, but for an overall evaluation the above factors are the most important.

2 Literature review

A large number of papers on hearing protector comfort are available in the literature. The following are some of the most important ones, particularly those by Casali, J. G., (1978), Pedro M. Arezes (2002) and Berger (1989).

Berger's paper gives an overview of comfort and also shows the inaccuracy problem associated with applying the British Standard BS 6344 - Part 1, for the average pressure calculation. It also shows the weak correlation between comfort and some relevant parameters. Detailed reviews of five published papers on comfort are also presented. These five studies are summarize here (2 to 6 below) and a further study published more recently by Rickie R. Davis (2008) is included together with other studies in order to illustrate a broader range of publications and the complexity associated with comfort evaluation.

1- Berger, E. H. & Mitchell, I., (1989).

This is probably one of the best papers published to date which deals with the comfort aspect of earmuffs. It illustrates the inaccuracies of the British Standard method (BS 6344 - Part 1). It shows that this standard method of calculating the cushion average pressure (CAP) generated between two flat surfaces does not generate results that bear a strong enough relationship with earmuff comfort. The authors revised five studies, considering also two flat surfaces (which will also be summarized herein) and show that the BS 6344 technique leads to inconsistent results which lack a sufficient relationship with earmuff comfort. The conclusion of this paper is that the comfort estimate should be derived from physical measurements of earmuff characteristics and it goes on to say that further research efforts should be directed towards the use of load cells (or contact pressure sensors, as presented in this paper) to sample pressure at the contact points and estimate the comfort index.

2- Acton, W.I., Lee, G.L. & Smith, D. J., (1976).

In this paper 12 earmuffs where assessed by 40 workers and the measurement of force and CAP at a cup separation of 150 mm was carried out. The preferred earmuff (52%) had a high force of 16.7 N, which indicates that earmuff comfort cannot be judged by force or average cup pressure, but pressure is an important parameter and should be kept as uniform as possible for high levels of comfort.

3- Lhuede E. P., (1980).

Twelve earmuffs were evaluated by twelve operators through six questions related to the parameters of earmuff tightness, heaviness, warmth, need for readjustment, ability to hear, comfort and acceptability. Also, the total force and CAP where measured at a cup separation distance of 145 mm. The author pointed out that there was very little evidence of a correlation between wearer acceptance and clamping pressure or force.

4- Tisserand, M. & Krawsky, G., (1972).

Ten subjects were asked to assess 24 earmuffs in short-term (< 5 minutes) and long-term (about one hour) tests. Numerous physical measurements were also carried out and the force and CAP were measured at a 148 mm separation distance. An earmuff with a CAP pressure of 4800 Pa received the highest comfort rating (9 out 24). Considering the data for the 24 earmuffs the correlations between comfort and CAP (-0.63) and comfort and headband force (-0.61) were both weak.

5- Sweetland, K. F., (1981).

Eight earmuffs and two earplugs were subjectively evaluated for comfort by forty-one British coal miners. Responses were correlated with the measured quantities, such as CAP at a 144 mm separation distance, total force, and cushion surface area and mass. A poor correlation was obtained between CAP and perceived pressure (+0.55). The author concluded that the irrelevance of the headband force and exerted pressure is contrary to the generally expected situation. However, the author found that the mass/unit of the CAP gave a good correlation with comfort.

6- **Casali, J. G., Lam, S. T. & Epps, B. W., (1987).**

Four earmuffs and two semi-aural devices were evaluated by naive subjects during REAT tests (Real Ear Attenuation at Threshold), using 23 pairs of adjectives. Force and CAP were measured at 143.5 mm. It was found that the top three earmuff comfort indices are statistically indistinguishable. Earmuffs with a CAP in excess of 4 KPa received very good subjective evaluations.

7- **Behar, A., (1984).**

Seven devices were evaluated including three earmuffs by 177 subjects. The headband force was measured using the norm ANS S3.19-1974. The author concluded that the results for headband force are contrary to what might be expected for comfort.

8- **Ivergard, T.B. & Nicholl, A. G., (1976).**

Ten earmuffs used in Swedish industrial plants were tested with the aim of developing reliable and valid methods to assess accident risk, ease and simplicity of use, and comfort. The authors found, firstly, that the short-term wear tests were highly predictive of the long-term tests (half-shift), except in relation to muff weight and cushion softness. They found that first impressions of the muff can be used to predict the long-term impressions. They concluded that an ideal muff is light and comfortable, but also must be easy to clean and maintain. The size of the muff should be large enough in width and depth to cover 95% of the worker's ear without applying pressure to the pinna. The muffs should contain sound-absorbent material to prevent resonances and reduce sound within the cup. There should be thick, soft cushions which can be taken on and off for cleaning. The headband should be wide and give enough pressure against the head to provide a good fit without discomfort. It should be noted that 85% of the subjects in the study were experienced earmuff wearers prior to the study.

9- Bhattacharya, S. K., Tripathi, S. R. & Kashyap, S. K., (1993).

These authors tested three earplugs and five earmuffs in two groups: college students and weavers. The subjects were given eight trials on each device and asked to give a binary comfortable / uncomfortable response. Of the subjects, 97-98% rated the earplugs as being comfortable. On the other hand, the five earmuffs were rated as comfortable by 50-90% of the subjects. Comfort scores were similar between the students and the weavers. The researchers identified some factors that seemed to correlate with comfort. They did not find any correlation with headband force and comfort. In fact, the two earmuffs with the strongest headband force were rated the most comfortable. They concluded that the following factors were important for comfort: oval-shaped cups which give a good fit around the pinna, more noise attenuation, larger space inside the cups to accommodate the pinna, foam cushions that conform to the head, and circumaural cushions which conform to the head to distribute the headband force. They concluded that the cushions are very important in terms of comfort.

10- Hus Y., Huang C., Yo C., Chen C. & Lien C., (2004).

These authors applied a four-part questionnaire where the third part deals with comfort. Ten frequent users gave responses for 14 comfort attributes (difficulty to converse, sense of oppression, itchiness, dirtiness, etc.). They created a COMFORT TESTER which measures headband force, air tightness (using compressed air injection and leakage measurements) and heat sink ability. The authors reported that the test results for the 28 earmuffs did not show any correlations between headband force, temperature and air tightness. The results for the subjects' reaction to temperature did not show any trend. Of the wearers, 80% described the headband force as having `no particular feeling' or being 'a little tight' for a headband force of under 10.5 N and for earmuffs weighing under 245 g.

11- Arezes, P. M. & Miguel, A. S., (2002).

Subjective evaluation of two earmuffs and two earplugs was carried out by 20 workers. The data obtained were treated statistically. The conclusion was that there was no significant difference between the two different types of ear protector in terms of the sensation of comfort.

12- Williams, W., (2007).

In this study 39 earmuffs were tested for headband force at a cup separation distance of 14.5 ± 2 cm. Also, the contact area was measured using a white sheet under the pre-inked cushion surface. The average clamping pressure for the 39 earmuffs was calculated to be 2.5 KPa with a standard deviation of 0.5 Kpa. The surface areas ranged from 31.7 to 54.3 cm^2 (mean 43.3 cm^2 and SD=5.3 cm^2). The author obtained contradicting results for the relation between clamping force or pressure and noise attenuation. The clamping pressure used was the calculated average, rather than the real pressure which we will present herein.

Related studies reported in other references given herein seem to report similar results.
All of these papers show the lack of a true comfort index based on the physical characteristics of the earmuff and also weak correlations between the total headband force or average pressure and subjective evaluation.

Evaluation using parallel surface widths of around 145 mm (similar to that used in the headband force measurements of ANSI S3.19-1974) allows a comparison between results and eliminates one of the complex variables, that is, the curvature of the human head. Also, the use of an artificial standardized head (ANSI S3.36-1985) allows the comparison of results, particularly for the new earmuffs with different left and right cushions. The use of real subjects may involve greater complexity of the anatomy of the human head and differences between human subjects, especially considering different race, gender, etc.

3 Contact pressure measurement technology

In the last few years contact sensors between two surfaces for the measurement of force or pressure have advanced to cover different fields including: Biomechanics, Body Mapping, Brake Pads, Bolted Joints, Clamping, Connectors, Clutches, Door Seals, Fuel Cells, Manufacturing, Gaskets, Golf Courses, Heat Sealing, Heat Sinks, Impact Studies, Injection Molding, Lamination Presses, Mattresses, Metal Stamping, Printed Circuit Boards, Seating, Solar Cells, Solid State Switches, Sprays, Squeegees, Tire Tread Footprints and others.

Pressure can be measured using a variety of instruments, including force-sensing resistors (FSRs), hydrocells, microcapsules, projection devices and capacitance transducers, as well as by critical light deflection. Many of these techniques can be used with an individual discrete sensor, or a matrix of multiple sensors with an array of sensors organized in rows and columns. Thus, matrix measurements can be used to assess the distribution of pressures acting over the entire surface. A major advantage when using a matrix measurement is that a larger surface area can be assessed at one time.

Two basic types of pressure sensors are available, resistive and capacitive. Other types, such as piezoelectric and ultrasonic, are also available but these are for specific applications.

Capacitive Sensors. A capacitive transducer consists of two plates made of a conducting material separated by a non-conducting or insulating layer called a "dielectric" layer". The transducer stores an electrical charge, and the two plates are compressed when force is applied, causing the distance between the plates to decrease. As the distance between the plates decreases the capacitance increases, and the resulting change in voltage is measured.

Resistance Sensors. These sensors comprise a very thin-layered device with metal patterns printed onto a conductive polymer layer embedded between two sheets. The conductive layer reduces resistance to the flow of electrons as the pressure between the two layers increases. This pressure between the two layers causes the resistance to decrease. The output of devices using this type of sensor technology can be either force or pressure. The force measured, however, is normal to the direction of the layers.

Others types of sensors are available, but are not calibrated and are used for qualitative analysis, such as microcapsules, projection devices with ink, hodoscopes for footprints, and critical light reflection.

The cost of these pressure contact sensors varies considerably, from homemade for a few US dollars to commercial system costing over thirty thousands US dollars.

These sensors, both resistive and capacitive, are non-linear and need calibrating at different levels. Resistive sensors can measure lower levels than capacitive sensors.

The range of pressures needed for earmuffs varies from zero, to be able to detect leakage of areas between the earmuff cushions and circumaural flesh of the human head, up to 17 KPa.

4. Comfort and overall indices calculations

The Single Associated Measured Index 'SAMI' was developed for quantification of the hearing protector overall quality. This index considers parameters related to comfort and noise attenuation, which are the most important two characteristics of a hearing protector. Many parameters are involved in the comfort quantification index, such as contact pressure and force distribution, contact area, center of gravity of the pressure, total force, mass of the protector, temperature and humidity distribution. Other parameters can also be considered in the overall index, such as noise attenuation, cost and lifetime of the protector. This overall measured quality index of earmuffs 'SAMI' is a single number measured quantitatively (not subjectively) which varies from unity for best to zero for worst quality. These measured indices will be correlated with subjective evaluations later in this paper. SAMI consists of Specific Associated Measurements indices; SAM1, SAM2, SAM3, etc., one for each variable, such as force distribution, center of gravity, contact area, weight, total force, noise attenuation, temperature and humidity.

4.1- Contact Pressure or Force Distribution Index (SAM1)

This index relates to the force distribution over the contact area. It is a single number index which describes the homogeneity of the force or pressure distribution.

If the force distribution is homogenous and uniform over all contact surfaces, then the hearing protector is very comfortable and SAM1 equals unity in this case. If the pressure is very high in a concentrated area, then there is a lack of comfort and the value for SAM1 decreases.

This index can be measured on a flat surface with the cup-cushion separation distance fixed at a value of 145.00 mm, as in the standard for the measurement of the headband force (ANSI S12.6-1997). Also, it can be measured on a dummy artificial normalized head (ANSI S3.36-1985) to avoid the human variation parameter and decrease uncertainty, or it can be measured on a real human head, a shown later in this paper.

SAM1 = 1- {Modulus |(sum of deviation of each element force)| / (total force+(n-2) average force)}

4.2- Center of Gravity of Force Index (SAM2)

This index defines the location of the total force applied which, for maximum comfort, should be at the geometric center of the muff where the headband force is transmitted to the cushions. It considers the specific locations of the distribution of pressures and is obtained by calculating the center of gravity of the force for each subarea and then determining the center of gravity for all subareas (s is the gravity position distance). If the center of gravity is not at the geometric center (not zero), this means that the force is not well distributed and there are forces concentrated in certain areas and not balanced by other forces in opposite areas.

SAM2 = s (position of center of gravity)/(max. position of center of gravity)

Where the max. position of center of gravity is the distance between geometrical centre and the extremity center of muff surface in the same direction.

4.3- Contact Area Index (SAM3)

This index considers the contact area in relation to the cushion total area. For a good quality hearing protector the contact area should be the same as the cushion total area and therefore there will be no leakage.

SAM3 = contact area measured on the head/cushion total contact area.

4.4- Weight of the Hearing Protector (SAM4)

The weight of an HPD affects the comfort directly, because the force of gravity presses the device against the skin, and indirectly, because the force required to hold the device in place increases as the weight increases. The following weight is suggested: an earmuff or an earphone mounted on a socket should weigh under 245 g, however, too little weight is not advisable since sound attenuation, at least for most materials, becomes lower as the weight decreases.

Measurement of the weight of 69 earmuffs shows values between 140 – 380 g, with an average value of 220 g and standard deviation of 57 g. Tisserand (1973) reported values of between 148 and 375 g for 25 earmuffs.

The human head has an average weight of 4.6 to 5 kg. Thus, an earmuff represents around 3 to 8% of the total head weight, which should not involve any significant discomfort based on the subjective study by Tisserand (1973).

According to Yeh-Liang (2004) earmuffs with less than 245 g are acceptable and comfort is weakly related to earmuff weight. However, a weak relationship can also be included in the comfort index, for example*:*

SAM4 = 1 for earmuffs with weight equal to or less than 245 grams

SAM4 = (245) / (weight of earmuff) for weight > 245 grams

4.5-Total Force (SAM5)

Although this value can be calculated from the contact pressure measurement (SAM1), it is very useful to calibrate the pressure measurement system with the total headband force measured using ANSI S3.19-1974. A comfortable earmuff, in general, should have a force below 12 N, and a lower limit may be around 8 N, otherwise the earmuff will have considerable leakage and the noise attenuation will decrease. Therefore, a weak index can be proposed based on 10 N being ‘most comfortable’.

SAM5 = (10) / (headband force) for headband force > 10 N
SAM5 = 1 for headband force less than or equal to 10 N

4.6- Noise attenuation (SAM6)

A good hearing protector combines high noise attenuation with high comfort levels (SAM1, SAM2 and SAM3 above).

SAM6 = NRR or NRRsf/ max. NRR or NRRsf (measured with the same standard) where NRR max or NRRsf max are the maximum value for similar types of earmuffs.

4.7-Temperature and Humidity (SAM7)

Ambient temperature can affect both the acoustic performance and the comfort of an earmuff. In some cases, a moderate softening of the material at body temperature may improve the conformability, thus improving the seal and comfort. Temperature may raise more serious problems with large hearing protectors, such as earmuffs and helmets, than with small ones. By providing heat insulation, they tend to raise the temperature of the head. In a cold climate this may be welcome but in a hot climate it becomes annoying. In addition to the discomfort caused by heat, evaporation of perspiration is almost impossible and buildup of humidity under the earmuff occurs. Muff cushions made, in part, of absorbent materials improve this situation. They have other disadvantages, however, since they typically cannot be dissembled and washed, and if they are not changed frequently they may become unhygienic. Consequently, earmuffs should cover the smallest possible area of the head surface, while still accommodating the pinna, which conflicts with the need for homogeneous pressure distribution. The area of contact between the helmet and the skin should also be kept to a minimum and, if possible, ventilation can be provided, especially in the case of muffs with a helmet. Different forms of SAM7 can be calculated. No proposal for SAM7 will be presented herein.

Overall Measured Quality Index of Earmuffs – SAMI

The overall index (SAMI) can be defined as:

$$SAMI = (SAM1)^{n1} . (SAM2)^{n2} . (SAM3)^{n3} . (SAM4)^{n4} . (SAM5)^{n5} . (SAM6)^{n6}$$

We can consider some of the above indices as being more important than others and give them greater weighting through the exponent n value.

Also, we can concentrate on the main comfort parameters only and, in this case, these are: the force distribution (SAM1), the center of gravity (SAM2), the area of contact (SAM3), the weight of the earmuff (SAM4) and total headband force SAM5.

In this paper measured results are presented for only SAM1, the pressure or force distribution index, which is the novel and most important one. Other indices can be calculated for each special case under investigation. Therefore SAM1 will be considered as the comfort index in this paper and all others SAMs will be considered unity. SAM1 will be compared with subjective evaluation of comfort.

5. Measurement on: Flat surface, normalized head and real human head

The measurement system used in this study is TEKSCAN I - Scan Lite *Enhanced* system, type 5101 with 1936 pressure resistive sensors (see Figure 1). The sensors are inside a plastic semi-hard sheet which cannot bend on the top of the ear, and therefore the ear area was cut out and some area of the pressure map was lost (see Figure 1-B). Also, we developed software to transform the color map pictures into numerical values to calculate the indices.

Attempts to use other sensors, like capacitive sensors with flexible surfaces, did not give good results, since the lowest pressure which can be measured is only around 600 Pa. We need to go as low a zero Pa to be able to detect leakage and non contact areas.

Figure 1-A

Figure 1-B

Figure 1-C

Figure 1: TEKSCAN measurement system with: (A) sensors connected to a notebook computer, (B) sensors with a hole for the ear position, and (C) showing the rigidity of the sensors.

Measurements are carried out on ten different earmuffs (see Figure 2) in three different situations; on a flat surface, on a dummy standardized head (ANSI S3.36 - 1985) and on a real human head.

Figure 2: The ten earmuffs used in this study.

5.1- Measurements on flat surface

Measurement of the pressure distribution is carried out on a flat surface. This surface is the same as that of the headband force measurement apparatus (ANSI S3.19-1974] with 140 mm width, as shown in Figure 3. The total force reading on the headband apparatus is the same as that calculated by the TEKSCAN system.

The TEKSCAN system is suitable for taking measurements on a flat surface. For each earmuff measurements were carried out in triplicate. The measured results for the pressure map are shown in Figure 4. The headband force varies slowly with time, and therefore the measurement was carried out for a period of 15 minutes. Figure 8 shows the results obtained for the force distribution index SAM1. The values for this index were 0.86 for the best protector down to 0.68 for the poorest.

Figure 3: Measurement on flat surfaces.

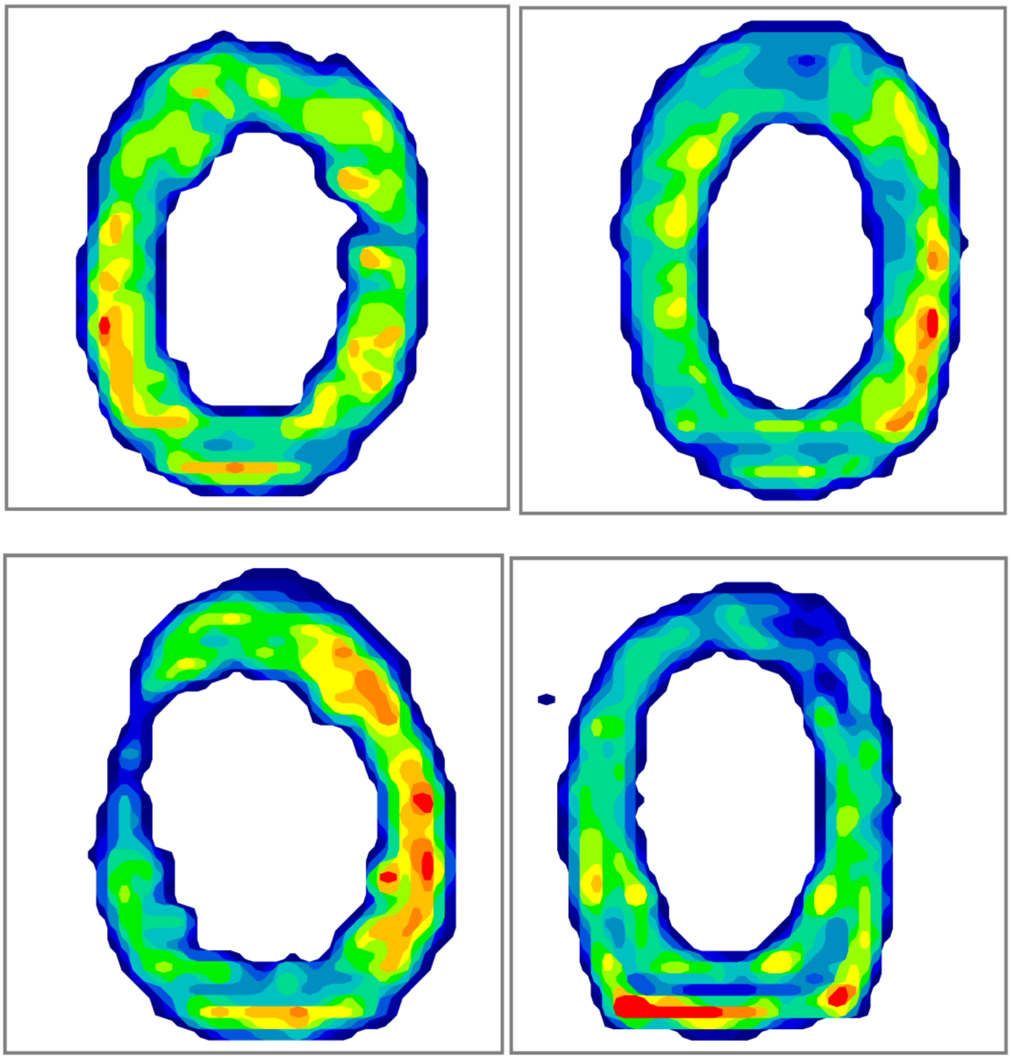

Figure 4: Typical contact pressure map obtained using the flat surfaces of the headband force measurement apparatus.

5.2- Measurements on Standardized Artificial or Dummy Head

Due to the great variation between subjects an artificial normalized head (ANSI S 3.36 - 1985) is used to determine the values for the index for the different earmuffs.
Figure 5 shows the standardized dummy head used which is a close replica of a real human head. The values for the force distribution index calculated using the colored map are shown in Figure 8.

Figure 5: Dummy Head Measurements.

5.3- Measurements on Human head

The measurements obtained using a real human head (see Figure 6) were taken for comparison with those of the flat surface and normalized dummy head measurements.

Figure 6: Human head measurements.

However, the subjective comfort parameter values usually exhibit large inter-subject and inter-laboratory variations, which makes it difficult to compare and select hearing protectors. Typical force distributions are shown in Figure 7 measured using a single subject only. The values for the force distribution index SAM1 are shown in Figure 8.

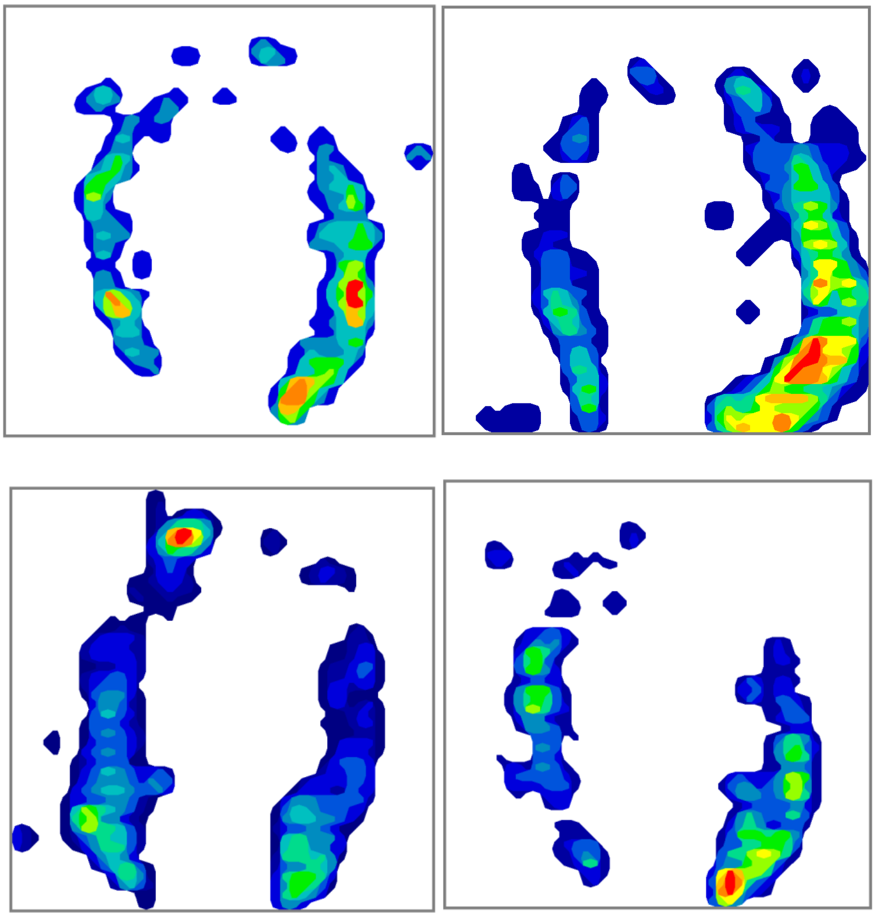

Figure 7: Pressure map measured on human head.

It is very interesting to note that one of the hearing protector devices (H) which has specified left/right muffs shows a lower index value for the flat surface measurements and nearly the same value as human head measurements, as expected, because of its non-symmetry characteristic.

Figure 8 shows the results for the flat surface, dummy (normalized) head and human head measurements.

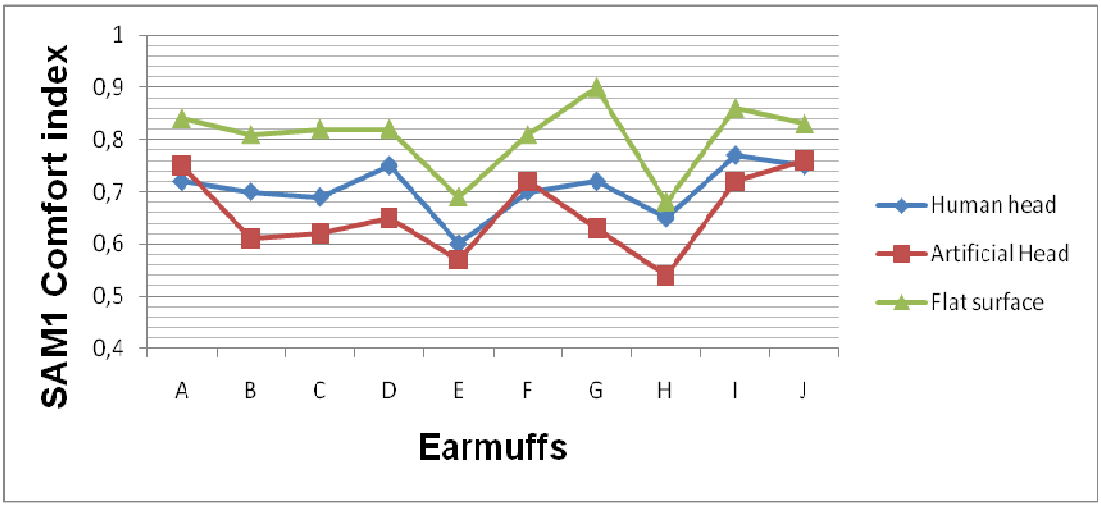

Figure 8: Comfort index SAM1 for flat surface, normalized head and human head for the ten earmuffs (A to J).

6. Subjective evaluation

Subjective evaluation was carried out for a short test period, since Ivergrad (1976) showed that short-term (2 to 3 minutes) tests were a valid basis for long-term user assessments.
The 10 earmuffs were tested by 20 subjects randomly chosen from the postgraduate students at UFSC - Acoustics and Vibration Laboratory, Brazil. Ages ranged from 20 to 35 and the time which each subject spent on the experiment was between 8 to 30 minutes (average 16.45 minutes and Standard Deviation 6.62 minutes). The subjects were asked to rank the 10 earmuffs from only the comfort point of view and each subject was permitted to attempt the assessment as many times as he/she wished. There was no time limit established. Each subject arranged the earmuffs on the table from worst to best in terms of comfort and was then asked to give them a grade from zero (worst comfort) to one (best comfort), using unit steps. Figure 9 shows the measurement results compared with those of the subjective evaluation.

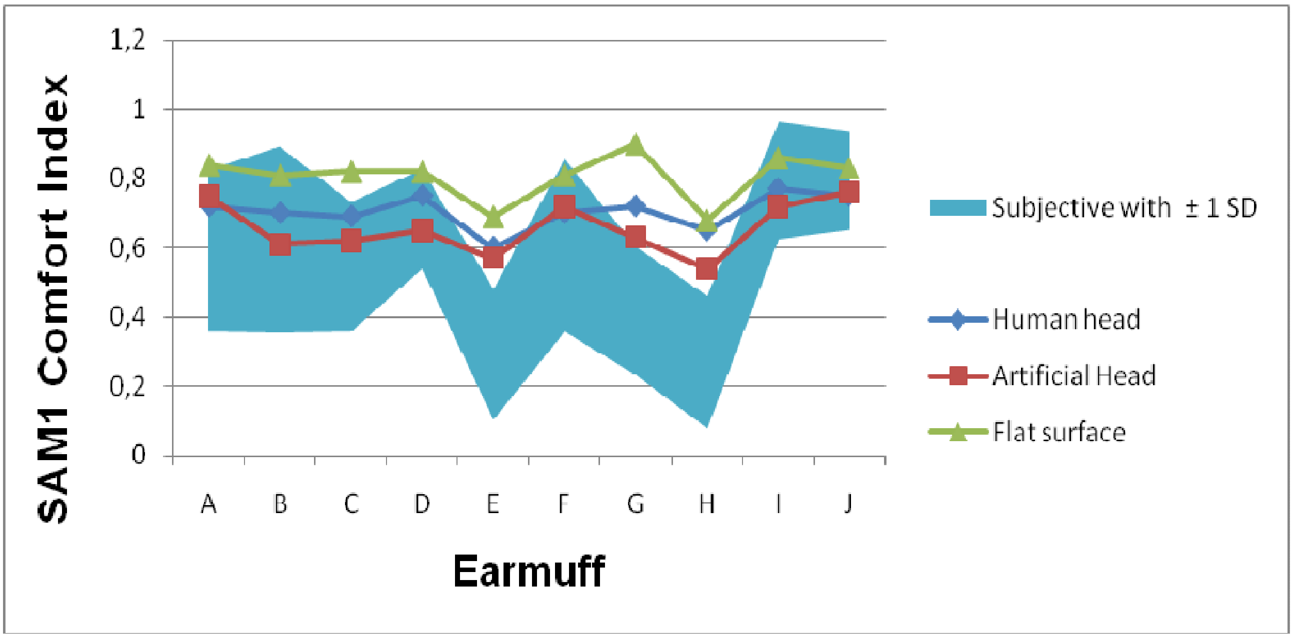

Figure 9. SAM1 Comfort index: comparison between subjective evaluation and measurements.

7. Discussion

The TEKSCAN measuring system gives very good results for the flat surface measurement only. The correlation results shown in Figure 9 show that measurements taken on a flat surface are not a good indicator of the force distribution on a real human head and for this reason they cannot be used even for relative comparisons. Furthermore, some hearing protectors may have different left and right earmuffs to fit the respective human ears. Poor correlations were obtained between the flat surface measurements and the subjective evaluations. The subjective evaluation gives lower comfort levels than the flat surface results in most cases.

Although the measurements of the force distribution index SAM1 on the normalized head and human head are not very accurate, since the TEKSCAN sensor is hard and gives false readings when it bends; the correlation with the subjective evaluation appears to be good. Most of the measurements are within the range of the average subjective results plus or minus one standard deviation. Only the human head results for the earmuffs E, G and H are outside the area, by a maximum of 20%, 16% and 29%, respectively. This is a very good correlation, considering that subjective evaluation is usually difficult to quantify.

It seems that The TEKSCAN measurement system did not make good contact with the surface when used on the artificial head or human head due to its rigidity.

8. Conclusions

The results obtained in this breakthrough study for the measurements of the contact pressure and force distribution between the earmuff cushions and circumaural flesh of the human head can explain the unexpected correlation between the measured total force and subjective evaluation in many studies reported in the literature which show that a higher headband force is more comfortable than a lower force. This novel study reveals that this is due to the details of the pressure distribution. A more uniformed distribution gives more comfort even for a higher total force. Therefore, the design of the headband's point of attachment and flexibility of the cushions is very important.

The results obtained in this study show that some commercially available pressure contact measurement systems, for example, TEKCSCAN (resistive-type sensor), can give good results only when measured on flat surfaces (not on the human ear or artificial head). Resistive sensors are probably better than capacitive sensors since they go down to near zero pressure values. Flat surface measurements are not good indicators of comfort, since the results obtained in this study show poor correlation with those of the subjective measurements. Also, flat surface measurements do not represent the real situation of the human head with its curved surfaces, especially for the new hearing protectors with specified left and right earmuffs. Unfortunately, to the best of my knowledge, there is no system commercially available in the market to carry out accurate measurements on a real human head.

In spite of the low accuracy of measurement on the normalized head and human heads using the TEKCSCAN system, and also the limited statistics using only one human subject, the results show good agreement with the subjective evaluation.

The author is currently developing a pressure contact measurement system for earmuffs on the human head made from smart materials.

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