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JASA ARTICLE

Morphologic clustering of earcanals using deep learning algorithm to design artificial ears dedicated to earplug attenuation measurement

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ABSTRACT:

Designing earplugs adapted for the widest number of earcanals requires acoustical test fixtures (ATFs) geometrically representative of the population. Most existing ATFs are equipped with unique sized straight cylindrical earcanals, considered representative of average human morphology, and are therefore unable to assess how earplugs can fit different earcanal morphologies. In this study, a methodology to cluster earcanals as a function of their morphologies with the objective of designing artificial ears dedicated to sound attenuation measurement is developed and applied to a sample of Canadian workers' earcanals. The earcanal morphologic indicators that correlate with the attenuations of six models of commercial earplugs are first identified. Three clusters of earcanals are then produced using statistical analysis and an artificial intelligence-based algorithm. In the sample of earcanals considered in this study, the identified clusters differ by the earcanal length and by the surface and ovality of the first bend cross section. The cluster that comprises earcanals with small girth and round first bend cross section shows that earplugs induced attenuation significantly higher than the cluster that includes earcanals with a bigger and more oval first bend cross section. © *2022 Acoustical Society of America*. https://doi.org/10.1121/10.0015237

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I. INTRODUCTION

Commercial disposable and reusable earplugs are widely used to prevent noise-induced hearing loss by attenuating the surrounding noise. To efficiently attenuate noise, the shape and material of the earplugs must match the earcanal morphology and provide a tight seal. However, due to the wide variability in humans' morphology, it is difficult for designers to achieve a universally acceptable product (Ferguson *et al.*, 2015). Thus, designing efficient and adapted earplugs that fit the widest range of earcanal morphologies remains extremely challenging. The one-size-fits-most approach has been used by manufacturers for many years to design earplugs. However, earplugs available in one size may result in either physical discomfort to extra-small earcanals due to a too-tight fit (e.g., pain inside the earcanal) or even functional discomfort (e.g., earplug falling out) and low attenuation to extra-large earcanals (Berger and Voix, 2022; Doutres *et al.*, 2022a). Today, more inclusive design approaches tend to be favored to ensure safety and comfort for all (not only in the hearing protection field, but also in clothing and architecture, for example). To ensure the best fit for the widest variety of users, a common solution consists in providing some earplug models in two or more sizes. For example, some models of foam earplugs are available in regular and small size. These sizes correspond to different earplug diameters, but targeted user groups of each size are not clearly identified on the packaging, making the selection and use of these earplugs much less convenient. As for premolded earplugs (usually made of flanges affixed to a stem) that may also be available in a range of sizes, it has been shown that the greater the number of flanges, the fewer the sizes required to fit the population (Berger and Voix, 2022). However, this is more a general trend than a practical designing rule. Designing for the outliers and introducing diversity into the design process requires inclusive methods and tools.

Acoustical test fixtures (ATFs) [that comply with the ANSI/ASA S12.42 (2010) standard] are good candidates for earplug design tools because they allow for rapid and repeatable attenuation measurements. However, existing ATFs are equipped with unique sized straight cylindrical earcanals in which some earplugs (for example, flangeless bullet-shaped earplugs of small diameter) cannot be properly fitted (Smith *et al.*, 1980; Berger, 1986). Furthermore, for a given earplug model to be tested, artificial straight cylindrical earcanals poorly capture the intra-individual variability in sound attenuation due to earplug fit (Benacchio, 2019) and cannot

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capture the inter-individual variability caused by large differences between human earcanal morphology (e.g., extra-small, regular, and extra-large earcanals). An ATF intended to test how earplugs can fit different users should therefore allow for a variety of shapes of earcanals (Berger, 2005). There is, thus, a need for more realistic artificial ears available in a variety of sizes and shapes, characteristic of targeted populations and instrumented to measure sound attenuation. It would allow for the design of earplugs that are better suited to a wide range of earcanal sizes and shapes or better identify the population for which the earplug is best suited.

The objective of this study is to develop a methodology to cluster earcanals as a function of their morphologies with the objective of designing artificial ears dedicated to sound attenuation measurement and to apply this methodology to a sample of Canadian workers' earcanals. In this context, having a comprehensive view of the earcanal morphology and its relation to earplug sound attenuation is crucial, but the number of studies on this subject is limited. Abel *et al.* (1988) found significant differences between women and men in attenuation of four commercially available earplugs: two foam earplugs and two premolded earplugs. The attenuations of earplugs available in a single size were lower when measured on women, whereas no gender effect was observed for earplugs available in a range of sizes. Gender differences in attenuation were, therefore, partly attributed to earcanal morphology differences between men and women. Abel *et al.* (1990) examined the correlation between the real attenuation at threshold (REAT) of three earplugs measured on 93 subjects and four morphologic parameters of earcanals estimated from the earmolds of these subjects. These parameters were (i) the areas of two cross sections of the earcanal estimated at the conchomeatal angle (first bend region) and at the cartilaginous-bony junction (second bend region), (ii) the conicity (called degree of funneling in the Abel *et al.* study) calculated as the ratio between these two section areas, and finally (iii) the tortuosity (which quantifies if the earcanal is more tortuous or straight), estimated visually. Results showed that a mismatch between the earcanal and the protector shapes could affect the attenuation. These earplug/earcanal mismatches were mainly attributed to the tortuosity and the conicity. Moreover, Abel *et al.* found that attenuation is linearly related to the cross-sectional area of the earcanal at the cartilaginous-bony junction. A gender effect was observed since the correlation between the cross-sectional area of the earcanal at the cartilaginous-bony junction and the attenuation was found positive for women and negative for men. The effects of the morphology on sound attenuation were found higher at medium frequencies (3150 Hz) than at low frequencies (500 Hz). Viallet *et al.* (2015) found similar tendencies on the effects of morphology on sound attenuation. Using a numerical approach, Viallet *et al.* were able to investigate the effects of earcanal morphology and acoustic leakage between the earcanal and earplugs. They showed that the important variability in the simulated sound attenuation of foam and silicone earplugs was mainly due to acoustic leakage for frequencies below 1 kHz and to the inter-individual variability of the earcanal morphology between 1 and 5 kHz. More recently, Mououdi *et al.* (2018) measured 918 external ear dimensions of 153 operational workers and found that the design of molded type earplugs should be improved to better match earcanal entrance shape and diameter to avoid inducing acoustic leaks. The literature, thus, suggests that the inter-individual variability in earcanal morphology contributes significantly to the inter-individual variability in sound attenuation. However, none of these studies provides a comprehensive description of earcanals through morphologic indicators quantified objectively together with their relations with attenuations of earplugs from the three earplug families: roll-down-foam, premolded, and push-to-fit. Thus, there is a lack of data and methods to design artificial ears representative of the wide variability in earcanal morphologies of a given population and able to mimic the sound attenuation measured on these earcanals.

In this work, a methodology to cluster earcanals as a function of their morphologies with the objective of designing artificial ears dedicated to sound attenuation measurement is developed and applied to a sample of Canadian workers' earcanals. The paper is organized as follows. Section II presents the morphologic and attenuation data acquisition and details the proposed methodology. Section III discusses the results and presents the limitations of this study. Finally, some concluding remarks are given in Sec. IV.

II. METHODOLOGY

The general description of the methodology used to cluster earcanals is shown in Fig. 1. In short, it starts with a verification of the main hypothesis of this work (step 0), followed by the clustering process (steps 1 and 2), and ends by the evaluation of the proposed clusters (steps 3 and 4).

Sections II A–II C describe the sample of participants and the acquisition of morphologic and attenuation data on which the clustering process is applied. Based on the literature, morphologic indicators supposedly correlated to attenuation are proposed and extracted from the sample of 242 earcanals. Attenuations of six different earplugs are objectively measured on these same earcanals. The clustering process is described in Sec. II D. In step 0 (Sec. II D 1), correlations between morphologic indicators and attenuation are evaluated to check that earcanal morphology is effectively related to inter-individual variability in sound attenuation. In step 1, a pre-processing of the morphologic dataset is performed: n combinations of morphologic indicators relevant for the clustering are selected following the rules detailed in Sec. II D 2. These combinations are then set as input to the clustering algorithm (see Sec. II D 3 about the k-means clustering algorithm), which is executed in step 2 to obtain $2n$ clustering proposals based on earcanal morphologies: n proposals of $k = 2$ clusters and n proposals of $k = 3$ clusters. The next two steps aim at choosing the clustering proposal that is the most relevant to be used as a basis to the

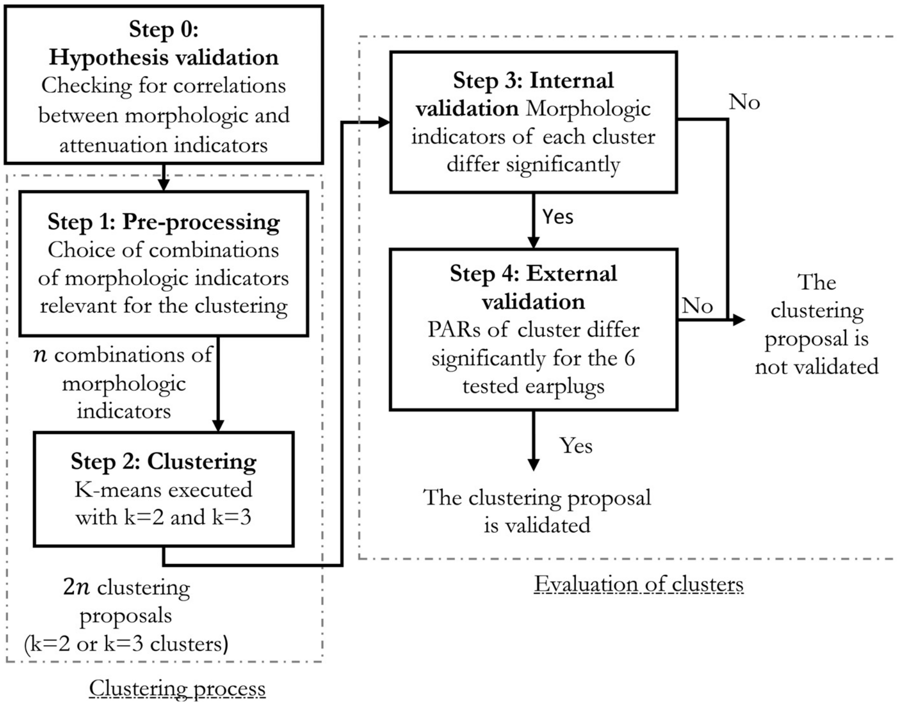

FIG. 1. Description of the clustering process.

design of realistic artificial ears representative of a sample of earcanals and dedicated to sound attenuation measurement. To do so, statistical analyses are performed to check that morphologic indicators are significantly different from one cluster to another (step 3, referred to as internal validation) and that personal attenuation rating (PAR) data are significantly different from one cluster to another (step 4, referred to as external validation).

A. Participants

A total of 121 persons (18 females, 103 males) working in three different Canadian companies participated in this study. Participants were between 21 and 64 years old [mean 46, standard deviation (SD) 10 years]. They were exposed to noise at work and wore earplugs before being involved in the study. They did not have antecedents of ear or neurological pathologies and did not have an important amount of earwax in their earcanals. This study uses the secondary data of morphologic and attenuation data collected during a field survey on earplug comfort (Doutres *et al.*, 2018) approved by the ethical committee of the École de Technologie Supérieure (ÉTS) (ethics certificate H20171101).

B. Morphologic data acquisition

1. Earcanal morphology sampling and scanning

The left and right earcanal morphology of each participant was obtained by scanning earmolds of earcanals. Earmolds were casted by two different custom earplug manufacturers: Laviolette Auditory Laboratory, Trois-Rivières, Canada (manufacturer #1) and Custom Protect Ear Inc., Surrey, Canada (manufacturer #2). The manufacturing process of custom earplugs involved remake of earmolds prior to the fabrication of custom earplugs. Among the 242 earmolds of this study (2×121 participants), 64 were casted and scanned by manufacturer #2 before being reworked. Manufacturer #2 casted and scanned 52 others after earmolds were remade. Remaking operations performed on these earmolds included cutting the lateral part of the earmold to keep only the earcanal plus the concha and a portion of helix, chamfering the medial part of the mold, and creating a hole to introduce acoustic filters. The remaining 126 earmolds casted by manufacturer #1 were slightly modified before being scanned in our laboratory using a 3D Scanner Einscan-SP (Hangzhou Shining 3D Tech Co., Hangzhou, China). Scans were hole-filled and smoothed using the EinScan-S Series version 2.6.0.8 software. Operations performed on these earmolds included cutting the lateral part of the earmold to keep only the earcanal plus the concha and a portion of helix. These simple operations did not modify the shape of the earcanal part of the mold.

The assumption is made that obtained earcanal scans accurately describe the participants' earcanal morphology: The modifications of the real earcanal morphology due to the acquisition process (i.e., the earmold casting process, the 3D scanner model, and the earmold reworking process) are considered negligible, and the difference between scans is only attributed to the difference between participants' earcanal morphology.

2. Extraction of morphologic indicators of shape and size of earcanals from scans

The earcanal is an "S-shaped" duct that extends between the concha on its lateral side and the tympanic membrane on its medial side. The cross section shape and size vary along the duct curvilinear axis (axis that passes

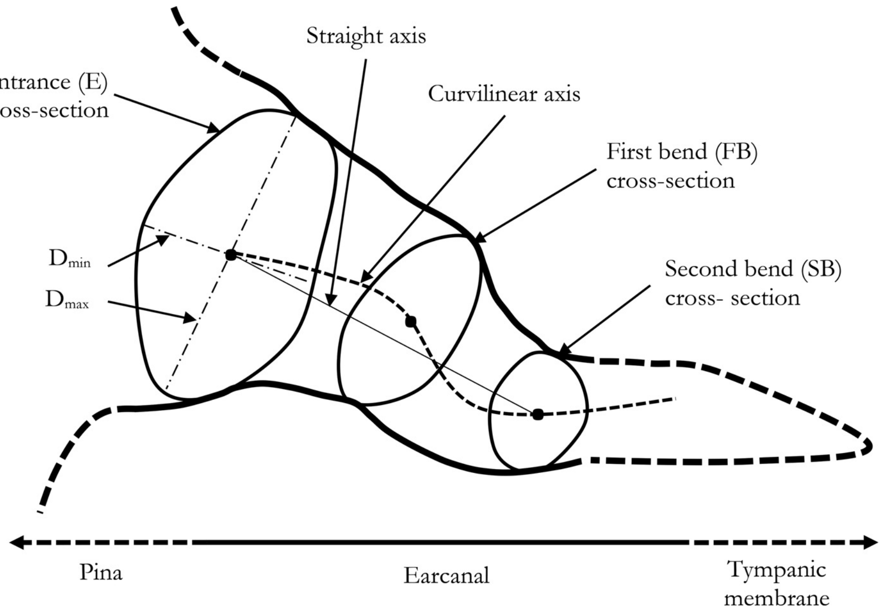

FIG. 2. Earcanal description. Dark thick solid lines, earcanal walls in the region of interest for this study. Dark thick dotted lines, earcanal regions that are ignored. Dark thin solid lines, reference cross sections of earcanal. Dark thin dotted line, the curvilinear axis of the earcanal. Thin mixed lines, the longest and shortest diameters of entrance cross section (used to calculate shape indicators as described below).

through the centroid earcanal cross sections, as seen in Fig. 2). As an overall trend, cross sections become smaller and more circular in the medial direction. Different characteristic sections are usually used to describe earcanal morphology (Lee *et al.*, 2018; Fan *et al.*, 2021; Abel *et al.*, 1990). In this study, three characteristic cross sections that cover all the earcanal portion accessible through the casting process are used: the entrance (E), the first bend (FB), and the second bend (SB). The entrance is usually defined at the base of the concha. The first bend is located a few millimeters after the entrance in the cartilaginous part of the earcanal. The second bend is positioned deeper in the earcanal and close to the cartilaginous-bony junction.

Two dimensions can be used to describe the morphology of the earcanal: size and shape. In this work, five features are chosen to characterize these two dimensions because they have been either shown to be relevant to the ergonomic design of an ear product (Lee *et al.*, 2018, Fan *et al.*, 2021) or correlated with earplug attenuation (Abel *et al.*, 1990). Each feature is quantified with one or several indicator(s). The calculation of all indicators belonging to the two aforementioned dimensions is based on the determination of the three cross sections E, FB, and SB. It is worth noting that these three characteristic cross sections may or may not be involved in the fit of the earplugs (since the earplug fit associated with the measured PAR is unknown). For example, cross section SB may not be involved in the fit of roll-down-foam earplugs for long earcanals or if the earplug is not fitted deeply inside the earcanal. Similarly, cross section E may not be involved in the fit of some push-to-fit-foam earplugs fitted deeply inside extra-large earcanals. The goal here is to describe the earcanal with morphologic indicators potentially related to earplug attenuation (based on the limited literature on the subject). The relevance of these indicators will be discussed in Sec. III B.

The position of each cross section (E, FB, and SB) in the earcanal is located using an objective methodology to avoid inducing any experimenter bias. This objective methodology is based on both the landmarks method and an objective method described below based on the positioning of cross sections perpendicular to the curvilinear axis of the earcanal. First, the curvilinear axis is extracted using the Stinson and Lawton (1989) method. For each earcanal, the curvilinear axis has two local maxima of curvature. The first local maxima of curvature (the closest to cross section E) and the second (the closest to the tympanic membrane) correspond to the position on the curvilinear axis of the FB and SB, respectively. Cross sections FB and SB are identified as the intersection between the earcanal walls and the planes perpendicular to the curvilinear axis at these two positions. Some earmolds are not casted deep enough in the earcanal to reach the SB. For these earmolds, the most medial section of the earmold is chosen as the section of the SB. To identify cross section E with a good repeatability, the Lee *et al.* (2018) methodology [also used by Fan *et al.* (2021)] is adapted. This method is based on four different points (landmarks) to define the earcanal cross section E. In the work presented here, cross section E is defined as the intersection between the earcanal walls and a plane perpendicular to the curvilinear axis that passes through the most posterior point at cross section E. This specific point defined in Lee *et al.* (2018) is chosen because it is the most easily identifiable one. Indeed, this point is located right at the junction between the concha and the earcanal, so in this zone, the earcanal surface has a high curvature. Curvy areas such as bumps and valleys can easily be located on a surface with a good repeatability.

The features used to describe the earcanal size are the length and girth. The earcanal length is characterized by the length of its curvilinear axis (in mm) between cross sections E and SB (because the bony portion of the earcanal was not accessible through the molding process). The girths of the three earcanal cross sections (i.e., E, FB, and SB) are described by two indicators that are either their area (in mm^2) or circumference (in mm).

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The features used to describe the earcanal shape are the tortuosity, the conicity, and the shape of cross sections. The tortuosity measures whether the earcanal is straight or crooked (i.e., more "S-shaped"). It is computed as the ratio between the curvilinear and the Euclidean length of the earcanal between the E and SB cross section centroids (see Fig. 2). A tortuosity equal to 1 indicates that the duct is perfectly straight, whereas a tortuosity greater than 1 indicates that the duct has an "S" shape. Conicity measures how much the earcanal shrinks in the medial direction. It is computed similarly as in Abel *et al*. (1990) as the ratio between the cross section E and SB areas (S_E/S_{SB}): A ratio close to 1 indicates that the earcanal is non-conical, whereas a higher ratio indicates that the earcanal significantly shrinks in the medial direction. The indicator of conicity computed as a simple ratio between the cross sections E and SB is an important simplification of the morphology of the earcanal. It simply describes the global diminution of earcanal cross section surface between the cross sections E and SB. A discussion about the relevance of this indicator can be found in Sec. III A. Finally, the shape of a cross section gives information about its circularity. Usually, cross sections between E and FB are triangular or elliptical, whereas those close to the SB are more circular. The isoperimetric ratio is used to evaluate the circularity of these sections. It is defined as the ratio between the area and the squared perimeter multiplied by 4 times π and varies between 0 and 1 (the closer to 1, the more circular the section). The aspect ratio of these cross sections is also computed to quantify their ovality. It is defined as the ratio between the longest and the shortest diameters of the cross section. Here, a diameter refers to a segment joining two opposite points on the cross section circumference and passing through its centroid. An example is shown in Fig. 2, where the aspect ratio of the cross section E is calculated as $D_{\min}/D_{\max}$.

All indicators are determined using Polyworks (InnovMetric Logiciels Inc., Québec, Canada) and MATLAB R2017b (MathWorks, Inc., Natick, MA). After a data inspection, two earcanals were discarded from the database because the curvilinear axis could not be computed with Stinson and Lawton's method. Because cross section FB determined with the proposed method intersects the concha, leading to very unusual shapes and very large perimeters, which yielded outliers for the statistical analysis, three more earcanals were removed.

C. Attenuation data acquisition

As mentioned previously, this study uses the secondary data of attenuation measurements collected during a field survey on earplug comfort. The original project included nine earplugs of different families and different manufacturers, but only six of them, for which attenuation measurements were carried out, are considered in this secondary study. Of these six earplugs, three belong to the roll-down-foam earplug family, one to the premolded family, and two to the push-to-fit foam family. Reference names of these earplugs can be found in Table I. Participants of the original project tested four different earplug models in their work environment for 7 weeks. At the beginning of each week, each worker had a one-on-one meeting with an audiologist to train him/her on the model of earplugs to be tested and to measure and verify the effective wearing of the earplugs. To this purpose, a field attenuation estimation system (FAES), the 3M™ E-A-Rfit™ Dual-Ear Validation System, was used as a training tool and attenuation data measurement. This system uses surrogate earplugs (see pictures in Figs. 3 and 4) to instantly measure and display a PAR compliant with the ANSI/ASA S12.71 (2018) standard. The PAR is the overall average A-weighted attenuation of an earplug for a given fitting in a large ensemble of representative industrial noise spectra (NIOSH 100) (Berger, 2010). This FAES system was chosen because it allows for quick measurements, which was an essential selection criterion since training sessions occurred during the participants' work shifts and had to be limited in time.

Two different PARs provided by the FAES are used in this study: the $PAR_{50\%}$ and the $PAR_{84\%}$. The $PAR_{50\%}$ is a median PAR that represents the most statistically probable value of the PAR (Berger and Voix, 2022) and is used in the following to cluster the earcanals (see Sec. II D). The $PAR_{84\%}$ is computed from the $PAR_{50\%}$ from which uncertainties are subtracted (such as the fit variability that accounts for the fact that the next time the person fits the hearing protector, he or she may do it differently) to give a more conservative estimate of the protection that is likely to be achieved on the field (Berger and Voix, 2022). It was therefore used by the audiologists during the training sessions as described in more detail in the next paragraph.

Details of the fit training procedure can be found in Martin *et al*. (2019) and are recalled here for completeness. The audiologist first reminded the worker how to put the earplugs in place, when to replace them, and how to check if

TABLE I. Earplug references.

Earplug family	Roll-down-foam			Premolded	Push-to-fit	
Earplug manufacturer's name	3M™ E-A-R™ Classic uncorded	3M™ Foam Earplug 1100	3M™ E-A-R™ E-Z-Fit™	3M™ E-A-R™ UltraFit™	3M™ E-A-R™ Push-Ins	3M™ E-A-R™ Push-Ins earplugs, 318-1008, with grip rings
Simplified name in this study	Classic foam	1100 foam	E-Z-Fit foam	Premolded	Push-ins	Push-ins-grip-rings

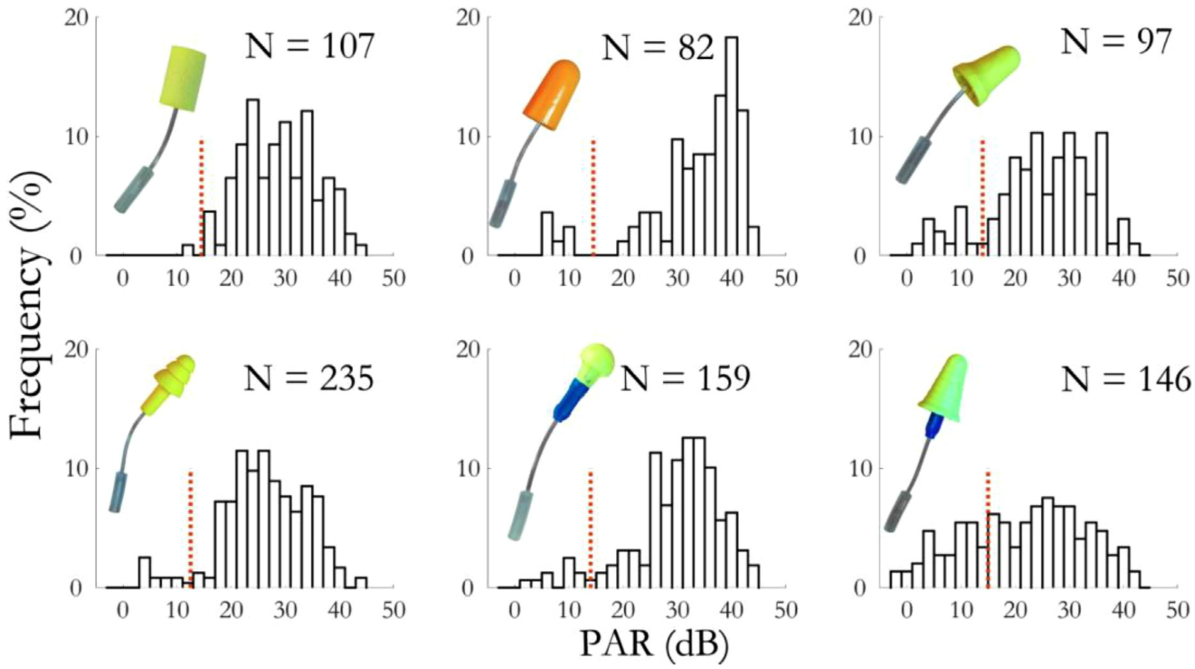

FIG. 3. (Color online) Distribution of the best PARs obtained during a fit training for the six earplugs (clockwise from top left): classic foam, 1100 foam, E-Z-Fit foam, premolded, push-ins, and push-ins-grip-rings. Orange dotted lines show half of the NRR of each earplug.

there was a proper fit. Then the worker put the surrogate earplugs in place himself (or herself) for a first PAR trial. If both ears had an initial $PAR_{84\%}$ of minimally 50% of the manufacturer's noise reduction rating (NRR) value (considered to as the first threshold value), the worker was considered adequately protected, and the individual training was over. If not, the worker was asked to adjust the earplugs for a second PAR trial, still aiming for 50% of the NRR. Since the $PAR_{84\%}$ data from the FAES take into account uncertainties that act as a security factor (Berger, 2010), a second threshold value of $PAR_{84\%} = 10$ dB was accepted. This threshold was chosen because most of the workers participating in the study had an average daily sound exposure level for 8 h less than 95 dBA. If the second trial reached at least this second threshold value of $PAR_{84\%} = 10$ dB for

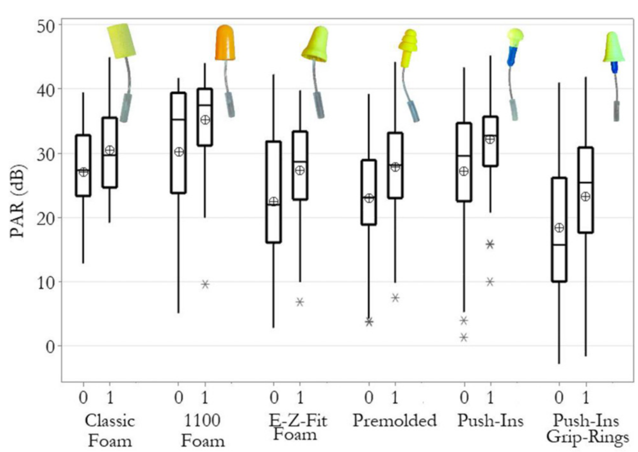

FIG. 4. (Color online) Box plot of the PAR of six earplugs for the two clusters of the best clustering proposal for $k = 2$.

each ear, the training was over. If this threshold value could not be obtained, a third placement was attempted by the audiologist. If this PAR trial was adequate, the worker was asked to replicate the proper placement to ensure that he or she was able to put the earplugs back in place (third trial, and more if needed). This is similar to the method described by Federman and Duhon (2016), where the participants learned successfully to reproduce the adequate placement (and similar PAR) after feeling the correct insertion by an expert. Finally, if both ears did not reach a $PAR_{84\%} \geq 10$ dB for all trials (fitted by the worker), the earplug model was considered unsuitable for this participant's ear(s). Most workers needed between one and three trials per session to properly fit their earplugs. For the roll-down-foam earplugs, six trials (for one ear) were sometimes needed. For a few participants, more than ten trials were required to reach the safe-threshold attenuation values of the training.

For each ear of each worker and for each earplug, the test data leading to the best $PAR_{84\%}$ were kept, and the research team exported the associated $PAR_{50\%}$ value as attenuation data to test the main underpinning hypothesis (see step 0 in Fig. 1) and to evaluate the clusters (see step 4 in Fig. 1). For ease of reading, in the remainder of the paper, the acronym "PAR" refers to the $PAR_{50\%}$. The distributions of $PAR_{50\%}$ for each earplug are plotted in Fig. 3. By considering both the fitting training process (similar for all participants) and the relatively high PAR values displayed in Fig. 3 (i.e., usually greatly superior to NRR/2; see Sec. III A for more details), the research team hypothesized that participants inserted their earplugs correctly so that the inter-individual variability in measured PARs can be mostly primarily attributed to differences in earcanals' morphology and not to other sources of variability related to the psychosocial characteristics of the participant and of his/her work environment (Doutres *et al.*, 2022b) (e.g., education, gender, support from family /colleagues, type of work, type and frequency of training, etc.). As mentioned previously, this hypothesis is checked in step 0 of the methodology presented in this paper (see Secs. II D 1 and III B).

D. Earcanal clustering

1. Step 0: Relations between earcanal morphology and sound attenuation

According to Sec. II C, the research team hypothesized that the inter-individual variability observed in the measured PARs is mainly induced by the differences in earcanal morphology. To check if this hypothesis is relevant (from the sample to which the methodology is applied in this paper), it is first checked whether correlations between morphologic data and attenuation data obtained during the training session exist. To do so, Pearson's correlation coefficients are computed between the morphologic indicator and PAR data using IBM® SPSS® Statistics 27.

2. Step 1: Choice of combinations of morphologic indicators relevant for the clustering

All relevant combinations of input morphologic indicators of the clustering algorithm to be tested are identified based on correlation between morphologic indicators. Taking into account correlations between morphologic data is crucial to avoid choosing a combination of morphologic indicators that are strongly correlated as an input to the clustering algorithm (Negrini *et al.*, 2020). Indeed, if two input morphologic indicators are strongly correlated, they would have a greater weight in the clustering analysis than other morphologic indicators. To account for the correlations between morphologic indicators, Pearson's correlation coefficient is computed for each pair of morphologic indicators using IBM® SPSS® Statistics 27. Additionally, scatter plots of each pair of morphologic indicators are also drawn to visually check whether non-linear correlations (not captured by the Pearson coefficient) between two morphologic indicators exist.

Following the correlation analysis, the combination of morphologic indicators to cluster earcanals is performed and based on three considerations. First, the correlation between two morphologic indicators in the same combination should not be higher than 0.8. Second, as some features (girth and cross section shapes) are described by several indicators, each combination must not have more than one indicator per feature (not to overweight a feature over the others). Third, each combination must include a girth indicator. This choice is motivated by the objective of building two or three artificial ears to test as many earplugs as possible. As several commercial earplugs are available in two sizes that differ in diameter, artificial ears should have appropriate earcanal girth to make it possible to test these earplugs.

3. Step 2: Clustering algorithm

The k-means clustering algorithm is chosen to classify earcanals. k-means is a partitional algorithm that classifies a set of data points in two phases (Na *et al.*, 2010). The first phase selects k centers randomly, where the value k is fixed in advance. In this work, k is forced to be less than 3 for practical and economic reasons associated with the objective of building artificial ears. The next phase is to take each data point to the nearest center. In this study, the Euclidean distance is used to determine the distance between each data point and the cluster centers. When all the data points are included in some clusters, the first step is completed, and an early grouping is done. This iterative process continues repeatedly until a goal function is minimal. Here, the goal function is the sum of the squared distances between each data point and its cluster center. An advantage of k-means over other clustering algorithms is that it minimizes the dispersion of data points around the cluster centroid and allows for determining the centroid of each cluster (Jain *et al.*, 1999). Knowing the centroid of each cluster is essential to find earcanal morphologies representative of each cluster (for example, an existing earcanal with dimensions close to the centroid of the cluster).

The k-means algorithm is executed with all n selected morphologic indicator combinations (previously selected in step 1) as inputs with $k=2$ and $k=3$ clusters and provides $2n$ clustering proposals (n for $k=2$ plus n for $k=3$). All these proposals are then evaluated individually to choose the best clustering of earcanals.

4. Steps 3 and 4: Clustering evaluation

The individual evaluation of each cluster is based on the following hypothesis: (i) it is possible to cluster two or three groups of workers' earcanals by combining relevant morphologic indicators; (ii) from these clusters, it is expected to observe significant differences in means showing that the level of PAR varies according to the morphologic indicators that characterize the groupings. The individual evaluation of each cluster proposal is, therefore, made using two consecutive validation procedures: (i) the internal validation (step 3) and (ii) the external validation (step 4). The internal validation is based on the following criterion: each morphologic indicator used to cluster earcanals must significantly differ from one cluster to another. This first criterion guarantees that artificial ears built based on these clusters will have significantly different morphologies. However, it does not guarantee that these artificial ears will enable the measurement of earplug attenuations being different and representative of the inter-individual variability in sound attenuation. A second validation procedure, referred to as the external validation, is therefore carried out. This validation is based on the following criterion: Mean attenuations (PARs) of the six earplugs of this study must significantly differ from one cluster to another. This second criterion is relevant because PAR data are checked to be, indeed, correlated with earcanal morphology (in step 0);

otherwise, significant differences in mean attenuation data of each cluster would not be expected.

Internal and external validations are performed using analysis of variance (ANOVA) and Bonferroni *post hoc* test with a significance level set at 0.05.

III. RESULTS AND DISCUSSION

A. Data description

Descriptive statistics of morphologic data measured on the sample of a population of Canadian workers consisting of 237 earcanals are summarized in Table II.

The earcanal size dimension is quantified through two features: the length and the earcanal girth. The length is comprised between 7.8 and 19.6 mm. The earcanal girth is quantified through two indicators, the area and the circumference, both measured at the three cross sections E, FB, and SB. Their mean (and SD) circumferences are, respectively, $C_E = 39.6$ mm (SD = 4.5 mm), $C_{FB} = 32.2$ mm (SD = 4.2 mm), and $C_{SB} = 28.6$ mm (SD = 4.6 mm), and their areas are $S_E = 104.3\ \text{mm}^2$ (SD = 22.3 mm^2), $S_{FB} = 75.6\ \text{mm}^2$ (SD = 19.0 mm^2), and $S_{SB} = 62.3\ \text{mm}^2$ (SD = 19.5 mm^2). As expected, the earcanal shrinks in the medial direction ($C_E > C_{FB} > C_{SB}$), confirmed by the conicity indicator $F_{E/SB}$ that is larger than 1. Other shape dimension indicators indicate that the earcanal becomes more circular in the medial direction ($IR_E < IR_{FB} < IR_{SB}$). The aspect ratios of cross sections E and FB are similar, whereas that of cross section SB is larger. Cross sections E and FB differ in terms of their iso-perimetric ratio but have similar aspect ratios. This is because cross section E is shaped like a triangle, whereas cross section FB (and SB) is shaped like an ellipse. Consequently, the aspect ratio and the iso-perimetric ratio are complementary to describe cross section E. Overall, this dataset confirms the general description of an earcanal given in Alvord and Farmer (1997).

The medians of the distribution of the best PARs obtained during the fit training vary between 23 and 37 dB depending on the earplug. The histograms of PAR data are plotted in Fig. 3 and show that except for with the push-ins-grip-rings earplug, most workers were able to obtain a high PAR during the training session. Indeed, most workers obtained PARs highly superior to 50% of the NRR values of the earplugs, which is a typical derating factor applied to the earplugs' NRR for estimating average protection levels for groups of users [see Table II of the CSA Z94.2–14 standard (CSA Group, 2014)]. Considering that the workers received about five trainings in the insertion of disposable and reusable earplugs during the field study (see Sec. II C) and that they obtained rather high PAR values after the training, it can be considered that the training sessions greatly reduced the inter-individual variability in sound attenuation related to psychosocial characteristics of the user and of his/her work environment (e.g., education, type and frequency of training, etc.) (Doutres *et al.*, 2022b). It is, therefore, reasonable to hypothesize that the inter-individual variability observed in the PARs measured is mainly induced by the differences in the morphology of the earcanals (this hypothesis is checked during step 0 presented in Sec. III B).

Low and negative PAR values observed on the push-ins-grip-rings earplug histogram suggest that a certain number of workers cannot fit properly the push-ins-grip-rings earplug, resulting in leaks and a poor attenuation. Large leaks may indeed act as a Helmholtz resonator and provide a gain effect in the low to middle frequency range (Berger, 2014). The fact that some workers were not able to obtain a safe PAR, even with a fit training, is consistent with the statement of Franks *et al.* (1996): "Not every person can wear every hearing protector. Some people may be unable to wear certain types of earplugs because of the shape or size of their earcanals."

B. Step 0: Relations between earcanal morphology and sound attenuation

Correlations between earcanal morphology and PARs are evaluated (Table III) to confirm that the inter-individual

TABLE II. Morphologic dimensions of earcanals and corresponding indicator names and descriptive values.

Dimension	Features	Indicator (s)	Earcanal region	Symbol	Mean	Median	SD	Min	Max
Size	Length	Curvilinear length (mm)	Between E and SB	L_{E-SB}	13.3	13.3	2.3	7.8	19.6
	Girth	Area (mm^2)	Cross section E	S_E	104.3	102.7	22.3	43.3	203.2
			Cross section FB	S_{FB}	75.6	73.2	19.0	33.8	124.8
			Cross section SB	S_{SB}	62.3	60.5	19.5	21.6	117.5
		Circumference (mm)	Cross section E	C_E	39.6	39.9	4.50	23.9	52.1
			Cross section FB	C_{FB}	32.2	32.4	4.2	21.4	42.4
			Cross section SB	C_{SB}	28.6	28.6	4.6	17.1	39.5
Shape	Sections' shape	Isoperimetric ratio	Cross section E	IR_E	0.83	0.84	0.07	0.62	0.96
		$4\pi(Surface/Circumference^2)$	Cross section FB	IR_{FB}	0.91	0.92	0.05	0.72	0.98
			Cross section SB	IR_{SB}	0.93	0.94	0.04	0.79	0.99
		Aspect ratio $D_{\min}/D_{\max}$	Cross section E	AR_E	0.64	0.62	0.12	0.32	0.96
			Cross section FB	AR_{FB}	0.62	0.61	0.12	0.35	0.98
			Cross section SB	AR_{SB}	0.72	0.71	0.11	0.45	0.99
	Tortuosity	Curvilinear length over Euclidian length	Between E and SB	T	1.06	1.06	0.03	1.01	1.19
	Conicity	Area of E over area of SB S_E/S_{SB}	Between E and SB	$F_{E/SB}$	1.81	1.68	0.61	0.89	5.48

TABLE III. Pearson linear correlation between morphologic parameters of earcanals and maximum PAR obtained with trained participant fitting the earplug himself/herself. Dark gray boxes highlight a correlation higher than 0.4, gray boxes highlight a correlation between 0.3 and 0.4, and white boxes highlight a correlation smaller than 0.3. Empty boxes indicate that the correlation between two variables is not significant at the level 0.05. *, the correlation is significant at the level 0.05 (bilateral); **, the correlation is significant at the level 0.01 (bilateral).

Morphologic parameters		PAR					
		Malleable			Premolded	Push-to-fit	
Position in the earcanal	Morphologic indicator	Classic foam	1100 foam	E-Z-Fit foam	Premolded	Push-ins	Push-ins-grip-rings
E cross section	C_E	−0.195*		−0.298**	−0.359**	−0.234**	−0.285**
	S_E				−0.302**	−0.246**	−0.257**
	AR_E		0.273*				
	IR_E	0.269**		0.330**	0.198**		
FB cross section	C_{FB}		−0.355**	−0.330**	−0.418**	−0.311**	−0.362**
	S_{FB}		−0.281*	−0.261**	−0.413**	−0.332**	−0.340**
	AR_{FB}	0.235*					
	IR_{FB}	0.228*	0.292**	0.327**			
SB cross section	C_{SB}		−0.335**	−0.308**	−0.478**	−0.347**	−0.410**
	S_{SB}		−0.226*	−0.270**	−0.470**	−0.352**	−0.381**
	AR_{SB}			0.304**			−0.182*
	IR_{SB}	0.228*	0.649**	0.306**			0.211*
Along earcanal	L_{E-SB}	0.223*				0.177*	
	$F_{E/SB}$				0.260**		0.221**
	T						−0.209*

variability in sound attenuation is related to the earcanal morphology and that the external validation described in Sec. II D is relevant on this dataset that characterizes a sample of Canadian workers' earcanals.

Table III suggests that the girths of FB and SB cross sections are moderately but significantly correlated to the sound attenuation of the push-to-fit and premolded earplugs (Pearson correlation coefficients less than 0.5). A significant correlation between these sections' girths and attenuation of two malleable earplugs is also found. These correlations are negative, which means that the larger the earcanal, the lower the attenuation. It can be hypothesized that a large earcanal leads to a lower compression of the earplug and surrounding tissues. As at low frequencies, the vibro-acoustic behaviour of the earplug coupled to the earcanal is governed by the equivalent rigidity of the system {earplug + earcanal skin} (Sgard *et al.*, 2011); a lower earplug/skin compression induces a lower equivalent rigidity and a lower sound attenuation. A lower mechanical pressure between earcanal skin and earplug may also introduce acoustic leakage.

Weak but significant correlations between the PAR and the shapes of cross sections FB and SB (IR_{FB}, IR_{SB} AR_{FB}, and AR_{SB}) are also found especially with roll-down foam earplugs, except for IR_{SB}, for which the correlation with the PAR of the 1100 foam earplug is fairly high (between 0.5 and 0.8). Correlations between section shape indicators and PAR are positive, meaning that the more circular the earcanal, the higher the PAR. It could be hypothesized that a circular earcanal allows for a better contact between earplug and earcanal walls, which avoids leaks between the earplug and the skin, leading to a higher attenuation. Lower but significant correlations between cross section E size and shape and PAR of earplugs are observed.

The conicity is only correlated to the attenuation of the premolded and the push-ins-grip-rings earplugs (the more conical the earcanal, the higher the PAR). These two earplugs have the most conical shapes of the six earplugs, and it can be hypothesized that they better match the geometry of conical earcanals than straight cylindrical earcanals (because the contact surface between the earplug and the earcanal would be higher in the first scenario). As described in Sec. II, the conicity computed as the ratio between the surfaces of the cross sections E and SB is an important simplification of the morphology: It does not describe how the cross section area changes in the medial direction (linearly or exponentially, for example), and it is computed between two cross sections that are not necessarily involved in the earplug fit (but correlated with earplug attenuation). In a preliminary study not shown in this paper, the conicity has also been computed as the ratio between the cross sections E – FB and FB – SB. These two additional indicators were, however, shown to be less relevant for this study because they were not correlated or were very poorly correlated to the earplug's attenuation. Finally, the conicity indicator computed between cross sections E and SB seems relevant to be included in the clustering process of this study because it is significantly correlated to the attenuation of two conical earplugs.

As for the parameters of length and tortuosity, they are poorly but statistically correlated to the attenuation of the classic foam and push-ins earplug (length indicator) and the push-ins-grip-rings earplug (tortuosity indicator). Conversely, Abel *et al.* (1990) found a high correlation between tortuosity and attenuation of earplugs. This could be due to the fact that Abel *et al.*, evaluated the tortuosity subjectively and selected only the 17th most straight and the 18th most twisted earcanals (over the 186 of his study) to compute Pearson's coefficient. Taking extrema values favors high linear correlation coefficients.

Finally, correlations between morphologic indicators and attenuations of the six earplugs given in Table III show that a given morphologic indicator is not equally relevant for the attenuation of different earplug models. This underlines the interest of choosing indicators that characterize the open earcanal (step 3, internal validation) and then studying the correlation with the attenuation (step 4, external validation) to build artificial ears dedicated to the measurement of the attenuation of a multitude of earplugs. Overall, correlations suggest that the morphologic variability of the earcanals induces a variability in the sound attenuation of earplugs correctly inserted. Therefore, it seems relevant to use attenuation data to validate a clustering proposal (step 4). It is reasonable to expect that mean attenuations of clusters classified using morphologic data will differ significantly.

C. Step 1: Choice of combinations of morphologic indicators relevant for the clustering

To choose relevant combinations of morphologic indicators as input for the k-means clustering algorithm, correlation coefficients are checked. Correlations between all morphologic indicators of this study are presented in Table IV.

Table IV shows that the two indicators of girth (i.e., circumference C and area S) of a given cross section have Pearson coefficients higher than 0.8 (see blue border boxes), indicating that they are highly correlated. Consequently, with the objective of choosing morphologic indicator combinations as input for the clustering algorithm, a given combination should include either the circumference or the area indicators but not both. Otherwise, the girth feature would have more weight than other features in a given combination. Correlations between the girths of SB and E cross sections are between 0.45 and 0.5 (orange border boxes), and the correlations between the girths of couples {FB, E} on the one hand and {FB, SB} on the other hand are close to 0.6 (green border boxes). Consequently, the girth of all the earcanal can be fairly well described by the FB cross section only. A similar conclusion can be drawn from the shape features of cross sections E, FB, and SB.

Considering that the earcanal girth is better represented by FB cross section than E and SB ones, it is selected to calculate girth (S_{FB}, C_{FB}) and shape indicators (IR_{FB}, AR_{FB}). Either C_{FB} or S_{FB} is chosen as cross section girth indicator and IR_{FB} or AR_{FB} as cross section shape indicator. In the sample of earcanals used in this study, there are 48 combinations of morphologic indicators that respect all criteria for the input combinations of the k-means algorithm. These 48 combinations of morphologic indicators are summarized in Table V. To check that there is no multicollinearity between morphologic indicators of the same combination, variable inflation factors (VIFs) are computed between all morphologic indicators. It is found that no VIFs are higher than 5 if the surface and the circumference of the cross section FB are not together in the list of morphologic indicators. As no combination includes these two morphologic indicators together, the research team concludes that there is no multicollinearity between morphologic indicators of a combination used as input for the clustering algorithm.

D. Steps 3 and 4: Cluster evaluation

As described in Sec. II D 4, the evaluation of earcanal clustering is based on a two-step evaluation for each clustering proposal: the internal and external validations. This two-step evaluation is performed for both $k=2$ and $k=3$ earcanal clusters.

Table V summarizes the validation process for the 48 proposals of earcanal classifications in two different clusters ($k=2$). The second column, "Combination of morphologic indicators," contains all of the 48 combinations of

TABLE IV. Pearson linear correlation between different morphologic indicators of earcanals. Dark gray boxes highlight a correlation higher than 0.5, gray boxes highlight a correlation between 0.3 and 0.5, and white boxes highlight a correlation smaller than 0.3. Empty boxes indicate that the correlation between two variables is not significant at the level 0.05. *, the correlation is significant at the level 0.05 (bilateral); **, the correlation is significant at the level 0.01 (bilateral).

S_E	AR_E	IR_E	C_{FB}	S_{FB}	AR_{FB}	IR_{FB}	C_{SB}	S_{SB}	AR_{SB}	IR_{SB}	L_{E-SB}	$F_{E/SB}$	T	
0.92**		−0.35**	0.67**	0.65**			0.49**	0.48**			0.16*		0.25**	C_E
	0.15*		0.66**	0.69**			0.47**	0.46**				0.19**	0.18**	S_E
		0.26**			0.28**	0.17**								AR_E
					0.55**	0.50**	−0.14*	−0.13*			−0.23**	0.18**	−0.23**	IR_E
				0.97**		−0.19**	0.61**	0.58**		−0.18**		−0.14*		C_{FB}
							0.61**	0.59**		−0.13*				S_{FB}
						0.43**								AR_{FB}
									0.32**	0.20**				IR_{FB}
								0.98**			−0.15*	−0.72**		C_{SB}
												−0.71**		S_{SB}
										0.43**				AR_{SB}
											0.25**	−0.14*		IR_{SB}
												0.13*	0.21**	L_{E-SB}
														$F_{E/SB}$

TABLE V. Cluster evaluation for $k = 2$ clusters. Gray boxes indicate that the p-value of the external validation ANOVA is significant at the level 0.05.

No.	Combination of morphologic indicators					Internally validated? t-test	External validation, p-value of the ANOVA on earplug PAR					
							Classic foam	1100 foam	E-Z-Fit foam	Premolded	Push-ins	Push-ins-grip-rings
1	C_{FB}					Yes	0.409	0.021	0.003	0.000	0.004	0.000
2	S_{FB}					Yes	0.823	0.031	0.011	0.000	0.005	0.000
3	C_{FB}	AR_{FB}				Yes	0.003	0.064	0.002	0.000	0.085	0.002
4	C_{FB}	$F_{E/SB}$				Yes	0.698	0.001	0.010	0.000	0.005	0.000
5	C_{FB}	T				No						
6	C_{FB}	L_{E-SB}				Yes	0.023	0.020	0.166	0.000	0.000	0.007
7	C_{FB}	IR_{FB}				Yes	0.001	0.017	0.000	0.000	0.061	0.042
8	S_{FB}	AR_{FB}				Yes	0.891	0.007	0.002	0.000	0.001	0.001
9	S_{FB}	$F_{E/SB}$				Yes	0.858	0.008	0.010	0.000	0.004	0.000
10	S_{FB}	T				Yes	0.972	0.025	0.009	0.000	0.006	0.000
11	S_{FB}	L_{E-SB}				No						
12	S_{FB}	IR_{FB}				No						
13	C_{FB}	AR_{FB}	$F_{E/SB}$			Yes	0.217	0.084	0.009	0.000	0.020	0.001
14	C_{FB}	AR_{FB}	T			Yes	0.002	0.055	0.022	0.000	0.190	0.001
15	C_{FB}	AR_{FB}	L_{E-SB}			No						
16	C_{FB}	$F_{E/SB}$	T			No						
17	C_{FB}	$F_{E/SB}$	L_{E-SB}			Yes	0.199	0.018	0.108	0.000	0.002	0.002
18	C_{FB}	T	L_{E-SB}			Yes	0.285	0.800	0.789	0.659	0.000	0.727
19	C_{FB}	IR_{FB}	$F_{E/SB}$			Yes	0.197	0.004	0.012	0.000	0.006	0.007
20	C_{FB}	IR_{FB}	T			Yes	0.005	0.016	0.003	0.000	0.031	0.177
21	C_{FB}	IR_{FB}	L_{E-SB}			Yes	0.022	0.011	0.012	0.000	0.001	0.009
22	S_{FB}	AR_{FB}	$F_{E/SB}$			No						
23	S_{FB}	AR_{FB}	T			No						
24	S_{FB}	AR_{FB}	L_{E-SB}			Yes	0.156	0.262	0.475	0.258	0.018	0.743
25	S_{FB}	$F_{E/SB}$	T			No						
26	S_{FB}	$F_{E/SB}$	L_{E-SB}			Yes	0.307	0.038	0.139	0.000	0.004	0.000
27	S_{FB}	T	L_{E-SB}			Yes	0.274	0.802	0.429	0.809	0.001	0.508
28	S_{FB}	IR_{FB}	$F_{E/SB}$			No						
29	S_{FB}	IR_{FB}	T			Yes	0.847	0.347	0.286	0.000	0.032	0.000
30	S_{FB}	IR_{FB}	L_{E-SB}			No						
31	C_{FB}	AR_{FB}	$F_{E/SB}$	T		No						
32	C_{FB}	AR_{FB}	$F_{E/SB}$	L_{E-SB}		No						
33	C_{FB}	AR_{FB}	T	L_{E-SB}		No						
34	C_{FB}	$F_{E/SB}$	T	L		Yes	0.428	0.572	0.411	0.011	0.000	0.084
35	C_{FB}	IR_{FB}	$F_{E/SB}$	T		Yes	0.345	0.006	0.092	0.000	0.013	0.080
36	C_{FB}	IR_{FB}	$F_{E/SB}$	L_{E-SB}		Yes	0.011	0.019	0.010	0.000	0.000	0.010
37	C_{FB}	IR_{FB}	T	L_{E-SB}		Yes	0.005	0.041	0.093	0.002	0.000	0.143
38	S_{FB}	AR_{FB}	$F_{E/SB}$	T		Yes	0.580	0.003	0.056	0.000	0.002	0.000
39	S_{FB}	AR_{FB}	$F_{E/SB}$	L_{E-SB}		Yes	0.535	0.017	0.068	0.000	0.002	0.000
40	S_{FB}	AR_{FB}	T	L_{E-SB}		No						
41	S_{FB}	$F_{E/SB}$	T	L_{E-SB}		Yes	0.263	0.394	0.197	0.005	0.000	0.023
42	S_{FB}	IR_{FB}	$F_{E/SB}$	T		Yes	0.857	0.014	0.090	0.000	0.002	0.000
43	S_{FB}	IR_{FB}	$F_{E/SB}$	L_{E-SB}		No						
44	S_{FB}	IR_{FB}	T	L_{E-SB}		No						
45	C_{FB}	AR_{FB}	$F_{E/SB}$	T	L_{E-SB}	No						
46	C_{FB}	IR_{FB}	$F_{E/SB}$	T	L_{E-SB}	Yes	0.004	0.072	0.093	0.000	0.000	0.163
47	S_{FB}	AR_{FB}	$F_{E/SB}$	T	L_{E-SB}	No						
48	S_{FB}	IR_{FB}	$F_{E/SB}$	T	L_{E-SB}	No						

morphologic data selected as inputs for the k-means clustering algorithm. The third column, "Internally validated? t-test," indicates whether the morphologic indicators of a given combination are statistically different from one cluster to another. If the answer is "Yes," the external validation is performed. The next six columns display the p-values of the ANOVAs performed on PAR of the six tested earplugs. If the six p-values are below the significance threshold of 0.05, the clustering proposal is considered validated according to the external validation procedure.

According to Table V, 29 combinations of morphologic indicators passed the internal validation step. Each of these

TABLE VI. Comparison of means of morphologic indicators between the two clusters of the best clustering proposal with $k = 2$.

Class	Earcanal number	Mean (SD)			
		C_{FB} (mm)	IR_{FB}	$F_{E/SB}$	L_{E-SB} (mm)
0	83	35.2 (3.2)	0.87 (0.057)	1.53 (0.42)	11.8 (2.0)
1	154	30.5 (3.6)	0.92 (0.04)	1.96 (0.64)	14.1 (2.03)

29 combinations is then tested with the external validation procedure with the objective to select a clustering proposal for which attenuations significantly differ from one cluster to another. This external validation is much more restrictive. Looking at gray boxes in Table V, it is worth noting that roll-down foam earplugs especially invalidate a lot of clustering proposals (this earplug is very restrictive for the external validation). The two push-to-fit earplugs and the premolded earplugs are much less restrictive. Indeed, the two push-to-fit earplugs invalidate only nine clustering proposals over the 29 combinations internally validated, whereas the classic foam earplug invalidates 20 clustering proposals. Interestingly, earplugs for which PARs are poorly correlated or not correlated to earcanal morphology invalidate more clustering proposals than earplugs for which PARs are moderately to highly correlated to earcanal morphology. Indeed, as the clustering is based upon morphologic classification, it is expected that earplug PARs significantly correlated to earcanal morphology may have significantly different means between clusters. This supports the interest of an external validation based on attenuation data in the objective of building artificial ears for attenuation measurements.

Finally, only two clustering proposals lead to significantly different attenuations for all six earplugs. These two combinations are $\{C_{FB} - IR_{FB} - L_{E\text{-}SB}\}$ (line 21 of Table V) and $\{C_{FB} - IR_{FB} - L_{E\text{-}SB} - F_{E/FB}\}$ (line 36 of Table V). These combinations are very close to each other, the only difference being the earcanal conicity, which is present only in the second combination. As the objective is to design artificial ears representative of and different between two clusters for a maximum of morphologic dimensions, it is the second proposal of clustering taking into account four morphologic dimensions that is retained (for $k = 2$ clusters).

For this kept clustering proposal $\{C_{FB} - IR_{FB} - L_{E-SB} - F_{E/FB}\}$, Table VI shows that the cluster 0 comprises the largest earcanals (leading to the lower attenuation as shown in Fig. 4) and the ones with the lower iso-perimetric ratios (also leading to the lower attenuation as presented in Fig. 4). Therefore, there is a double effect of morphology on attenuation for this clustering proposal: The most circular and smallest earcanals have the best attenuation, whereas the more oval and larger earcanals have the poorer sound attenuation. This double effect explains why attenuations of cluster 0 and cluster 1 differ significantly.

It should be noted that for the sample of earcanals presented here, the cluster of largest earcanals also comprises the shortest earcanals. Finally, the most conical and straight cylindrical earcanals are grouped in cluster 1 and cluster 0, respectively.

For this clustering proposal, the PAR significantly differs from one cluster to another for the six earplugs as shown in Fig. 4.

Regarding the evaluation of clustering proposal for $k = 3$, the same two-step validation process as for $k = 2$ is followed. The only difference is that the internal validation is based on the Bonferroni *post hoc* test. This is motivated by the fact that there are now three clusters of earcanals. This *post hoc* test allows a pairwise comparison of clusters. The results of the external validation for the 12 combinations that passed the internal validation are listed in Table VII.

As for the external validation, an ANOVA is performed on earplug PARs. The same trends as for $k = 2$ clusters are observed. The two push-to-fit earplug PARs significantly differ for most of the clustering proposals. All clustering proposals internally validated are also validated with the PAR for the premolded earplug. Foam earplugs, however,

TABLE VII. Cluster evaluation for $k = 3$ clusters. Only clusters that satisfied the internal validation (Bonferroni *post hoc* test) are plotted in this table. Gray boxes indicate that the p-value of the external validation ANOVA is significant at the level 0.05.

No.	Combination of morphologic indicators				External validation p-value of the ANOVA on earplug PAR					
					Classic foam	1100 foam	E-Z-Fit foam	Premolded	Push-ins	Push-ins-grip-rings
1	C_{FB}				0.015	0.135	0.227	0.000	0.001	0.029
2	S_{FB}				0.907	0.001	0.009	0.000	0.000	0.000
3	C_{FB}	IR_{FB}			0.070	0.051	0.004	0.000	0.028	0.020
4	C_{FB}	$F_{E/SB}$			0.317	0.006	0.007	0.000	0.004	0.001
5	C_{FB}	T			0.586	0.061	0.001	0.000	0.015	0.000
6	C_{FB}	L_{E-SB}			0.192	0.023	0.003	0.000	0.009	0.002
10	S_{FB}	T			0.524	0.169	0.002	0.000	0.004	0.000
15	C_{FB}	AR_{FB}	L_{E-SB}		0.022	0.173	0.021	0.000	0.026	0.032
16	C_{FB}	$F_{E/SB}$	T		0.609	0.034	0.012	0.000	0.057	0.000
21	C_{FB}	IR_{FB}	L_{E-SB}		0.045	0.005	0.017	0.000	0.004	0.002
32	C_{FB}	AR_{FB}	$F_{E/SB}$	L_{E-SB}	0.344	0.159	0.027	0.000	0.030	0.003
33	C_{FB}	AR_{FB}	T	L_{E-SB}	0.006	0.754	0.019	0.000	0.003	0.064

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TABLE VIII. Comparison of means of morphologic indicators between the three clusters of the best clustering proposal with $k = 3$.

Class	Earcanal number	C_{FB} (mm)	IR_{FB}	L_{E-SB} (mm)	
0	92	28.5	0.93	12.9	Mean
		28.2	0.93	13.0	Median
		2.6	0.03	1.6	SD
1	69	33.4	0.91	15.7	Mean
		33.5	0.91	15.7	Median
		2.9	0.04	1.3	SD
2	76	35.4	0.88	11.5	Mean
		35.1	0.88	11.7	Median
		3.0	0.06	1.6	SD

invalidated several clustering proposals, especially the classic foam earplug, which invalidated 8 of the 12 internally validated clustering proposals.

Finally, only one combination of morphologic indicators provides clusters that meet both the external and the internal validation: $\{C_{FB} - IR_{FB} - L_{E-SB}\}$ (line 21 in Table VII). The unique combination of morphologic indicators ($\{C_{FB} - IR_{FB} - L_{E-SB}\}$) that satisfies both validation criteria for $k = 3$ clusters also meets both criteria for $k = 2$ clusters (see line 21 of Table V).

As seen in Table VIII, the number of earcanals per cluster is well balanced for this clustering proposal. Again, there is a double effect of morphology on attenuation. Cluster 0 includes the earcanals for which the girth is the smallest (higher attenuation as seen in Fig. 5) and earcanals with the highest iso-perimetric ratios (higher attenuation as seen in Fig. 5). Cluster 2 comprises the largest and most oval earcanals. Finally, cluster 1 is in the middle of these two clusters for these two indicators (C_{FB} and IR_{FB}). This double effect explains why attenuations of clusters 0, 1, and 2 differ significantly.

Figure 5 shows boxplots of the best PARs obtained during the fit training for the three clusters and each earplug. The sound attenuations of earplugs in cluster 0 are, overall, higher (significantly at the level 0.05) than those in cluster 2.

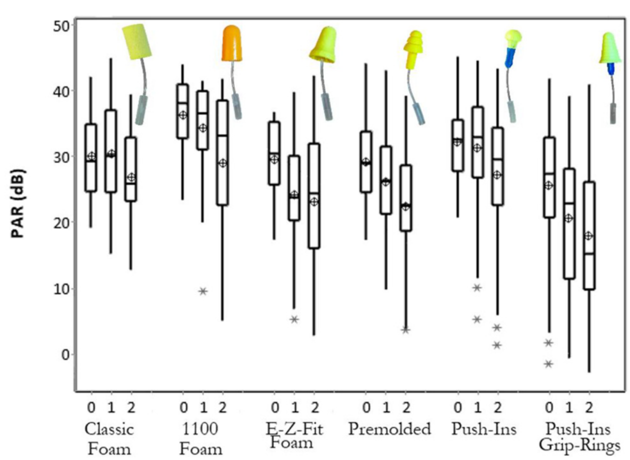

FIG. 5. (Color online) Box plot of the PAR of six earplugs for the three clusters of the best clustering proposal for $k = 3$.

However, sound attenuations of earplugs in cluster 1 do not necessarily differ from those in other clusters. It is important to recall that attenuations have not been used as an input to cluster earcanals. The difference of attenuation of different clusters is just a consequence of the correlation between morphology and attenuation. A Bonferroni *post hoc* test (not shown in this paper) has been conducted for sound attenuations of all earplugs. For the premolded earplug, attenuations in each cluster significantly differ from one another (at the level 0.032 between clusters 0 and 1, level 0.006 between clusters 1 and 2, and level <0.001 between clusters 0 and 2). Consequently, with the objective to build artificial ears for the measurement of attenuation on a maximum of earplug types, it seems relevant to use three different clusters of earcanals. Finally, it is this final clustering proposal, obtained with the k-means algorithm with morphologic indicators $\{C_{FB} - IR_{FB} - L_{E-SB}\}$ and $k = 3$ different clusters of earcanals that seems the most relevant to help in the design of realistic artificial ears dedicated to earplug measurement attenuation.

To check that the final k value of 3 achieves an optimal solution, complementary analyses (not associated with the objective of building two or three artificial ears) have been conducted. The same clustering methodology as for $k = 2$ and $k = 3$ has been applied with $k = 4$. For four clusters, only two combinations of morphologic indicators successfully passed the internal validation ($\{S_{FB}\}$ and $\{S_{FB}; AR_{FB}\}$). Neither of these two combinations successfully passed the external validation. This strongly suggests that the final clustering proposal obtained with $k = 3$ clusters is an optimal solution.

E. Limits

Limitations of the clustering methodology and its application to a sample of earcanals are identified in this section.

The proposed methodology being applied on a limited number of earcanals, statistical limitations associated with generalizing results from a sample apply.

A single process of clustering and validation procedure is performed to cluster earcanals. Other clustering algorithms and/or statistical tests to validate clusters could have been used and may have led to another clustering structure of earcanals. The method presented here makes it possible to select a clustering of earcanals relevant as a basis for the design of artificial ears dedicated to sound attenuation measurement.

The description of earcanals' morphology is here limited to 15 morphologic indicators (seven size indicators and eight shape indicators) that describe the earcanal portion where the earplugs are supposed to be fitted (between the entrance and the second bend). It is, therefore, assumed that these indicators are sufficient to comprehensively describe the earcanal morphology. Other anatomical properties that may be also responsible for inter-individual variability in sound attenuation, such as mechanical properties of ear tissues, the position of the cartilaginous/bony junction, or eardrum impedance, are not considered here (note that some of them can be difficult to determine in the field or even impracticable).

Comparison of earcanal morphologic differences between studies is complicated because methods to extract morphologic indicators differ and are not always objective. In this paper, the proposed method to extract the morphologic indicators has been designed to be as objective as possible (i.e., reducing the number of manually placed landmarks to locate characteristic cross sections of the earcanal). However, this method is based on the use of cross sections perpendicular to the curvilinear axis, which may not be equally relevant for all earplugs considered in this study. For example, the radial axis about which the flanges of a premolded earplug extend might not be centered on the curvilinear axis.

The earplug insertion depth is unknown, and a better knowledge of the position of each earplug in each ear could have been helpful to identify the most relevant cross sections to be correlated with the measured sound attenuation.

In addition, the type of training used in the original field study has led to a PAR value that was considered high enough to assume that that measured inter-individual variability in PAR could mainly be attributed to the morphologic differences between earcanals. However, it can be hypothesized that the correlations between morphologic indicators and PAR could have been higher if the training session had been designed specifically for this study (or if an experimenter fitting had been performed for PAR measurements) and, thus, would have targeted the maximum PAR achievable for a given earplug.

IV. CONCLUSION

Most existing ATFs dedicated to earplug sound attenuation measurement are equipped with unique sized straight cylindrical earcanals, considered as representative averaged morphology of humans and, thus, are unable to assess how earplugs can fit different earcanal morphologies.

In this paper, a methodology to cluster earcanals as a function of their morphologies with the objective of designing artificial ears dedicated to sound attenuation measurement is developed and applied to a sample of Canadian workers' earcanals. Morphologic indicators were measured/computed on earmolds of earcanals, and attenuation of six different earplugs was measured on these same earcanals. An artificial intelligence-based algorithm and statistical analysis were used to assess earcanal clusters that were the most relevant to help in the design of realistic artificial ears dedicated to earplug attenuation measurement. The morphologic data of the population sample considered in this study proved to be consistent with the literature, and significant correlations between some morphologic indicators and attenuation of earplugs were found. Considering this population sample, the best clustering proposal was obtained using the three following morphologic indicators as input for the *k*-means algorithm: (i) circumference of the first bend cross section, (ii) isoperimetric ratio of the first bend cross section, and (iii) length between the entrance and the second bend. This clustering proposal consists of three different clusters of earcanals. It was found that the cluster that comprises earcanals smallest in girth and the most circular is also the cluster where measured PARs are the highest, whereas the cluster that includes the largest and most oval earcanals has low measured PAR. This observation is consistent with the correlation morphology/attenuation both observed in the literature and confirmed by this study.

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