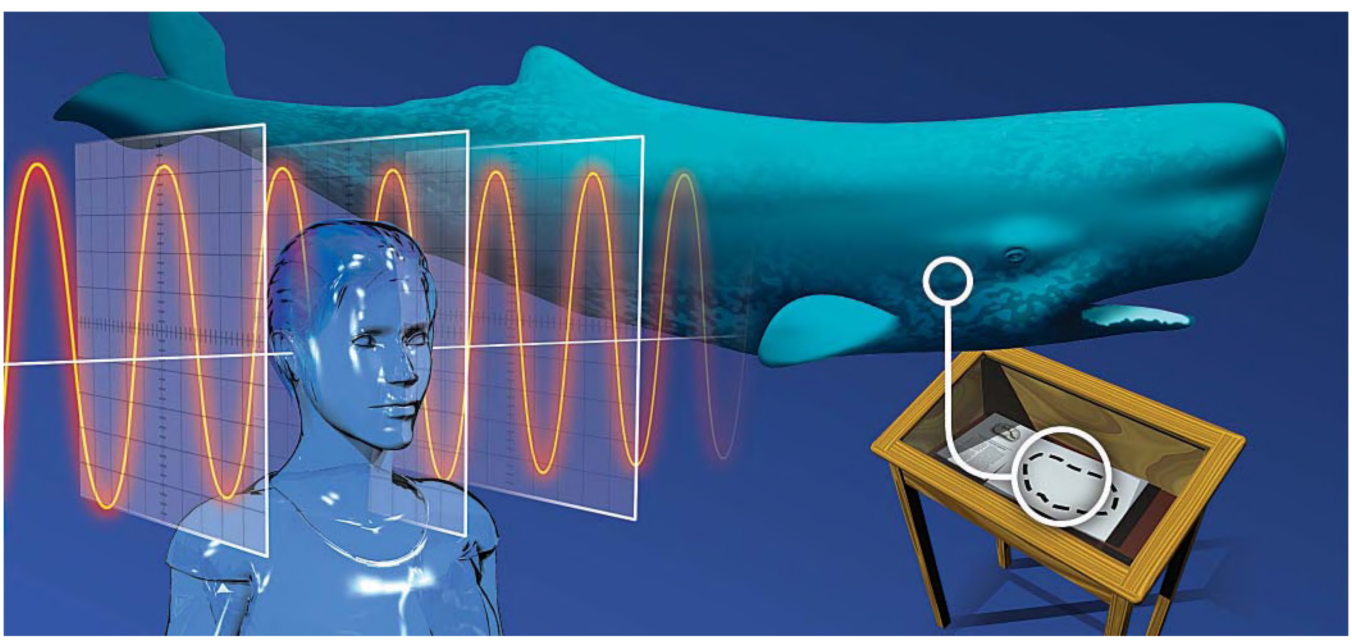
ISSN 0711-6659

# canadian acoustics
# acoustique canadienne

Journal of the Canadian Acoustical Association - Journal de l'Association Canadienne d'Acoustique

DECEMBER 2011 DECEMBRE 2011
Volume 39 -- Number 4 Volume 39 -- Numéro 4





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## PRESIDENT'S MESSAGE / MESSAGE DU PRÉSIDENT

It has been a pleasure to host Acoustics Week in Canada 2011 in Quebec City this past October. All in all, 115 presentations were delivered covering all aspects of acoustics and vibration, and over 190 attendees participated in the technical program, standards meeting and/or exhibitor show. Of note, 70 attendees registered as new members of the Association, including 45 students. A special mention goes to our plenary speakers: Isabelle Millette and Maurice Bhérer on cochlear implants, Jocelyn Robert on sound and artistic creativity, and Alain Berry on acoustic imaging for their captivating presentations. The conference concluded with a technical tour of the recently renovated concert hall Palais Montcalm. Organized by Jean-Philippe Migneron in collaboration with Gaétan Pageau and Philippe Poulin, respectively director of operations and technical chief of Palais Montcalm, more than 25 participants tirelessly scanned the main hall, backstage and every possible corner of the building to satisfy their acoustical passion for architectural acoustics, noise control, and of course, music! Finally, I would like to thank the members of my organizing committee: Hugues Nélisse and Jérémie Voix as Technical Co-Chairs, André L'Espérance as Exhibition Coordinator, Jean-Philippe Migneron and François Bergeron for Conference logistics and special events, Nicolas Ellaham as Webmaster as well as many others who provided assistance and made the conference a great success.

Acoustic in Canada 2012 will be held in another beautiful setting in Banff Alberta, October 10-12. The conference organizing committee is led by our Past President, Stan Dosso, and we can look forward to another exciting annual meeting in terms of technical content and social events. It will be the first time our association meets in Banff! Please mark it down in your calendar, and consult the current and future issues of Canadian Acoustics or the website for more information.

Many thanks to Rich Peppin (Scantek Inc.) who just completed a six-year term on the Board of Directors and provided invaluable help with his perspective as acoustical equipment supplier. The good news is that Rich remains Advertizing Coordinator for Canadian Acoustics. At the same time, I welcome our newly elected Director Kathy Pichora-Fuller (University of Toronto Mississauga), who has a long history

Il fut un grand plaisir d'accueillir la Semaine canadienne d'acoustique 2011 à Québec en octobre dernier. Au total, 115 communications orales ont été présentées dans les différents domaines de l'acoustique et des vibrations et au-delà de 190 personnes ont participé aux séances scientifiques, activités de normalisation ou à l'exposition technique. Un fait à signaler, 70 participants se sont inscrits comme nouveaux membres de l'Association, y compris 45 étudiants. Une mention toute spéciale va à nos conférenciers pléniers: Isabelle Millette et Maurice Bhérer en implants cochléaires, Jocelyn Robert en créativité sonore et Alain Berry en imagerie acoustique, pour leurs captivantes présentations. Le congrès s'est terminé par une visite technique de la rénovation de la salle de concert du Palais Montcalm. Organisé par Jean-Philippe Migneron en collaboration avec Gaétan Pageau et Philippe Poulin, respectivement directeur des opérations et chef des services techniques du Palais Montcalm, plus de 25 participants ont inlassablement scruté l'acoustique du hall principal, les coulisses et tous les racoins de l'édifice afin de satisfaire leur passion pour l'acoustique architecturale, le contrôle du bruit, et bien sûr, la musique! Enfin, je tiens à remercier les membres de mon comité organisateur: Hugues Nélisse et Jérémie Voix comme directeurs techniques, André L'Espérance à titre de coordonnateur de l'exposition technique, Jean-Philippe Migneron et François Bergeron pour les aspects de logistique et événements spéciaux, Nicolas Ellaham en tant que webmestre ainsi que plusieurs autres qui ont fourni une aide précieuse lors du congrès pour en faire un franc succès.

La Semaine canadienne d'acoustique 2012 se tiendra dans un décor des plus enchanteur à Banff en Alberta du 10 au 12 octobre prochain. Le congrès sera mené par le Président sortant de l'Association, Stan Dosso, et nous pouvons anticiper un congrès des plus passionnants encore l'an prochain tant au niveau du programme scientifique que des événements sociaux. Ce sera la toute première fois que notre association se rencontra à Banff! Veuillez inscrire dès maintenant cet événement dans votre agenda et consulter l'Acoustique canadienne et le site internet de l'association pour de plus amples renseignements et les mises à jour.

Un grand merci à Rich Peppin (Scantek Inc.) qui vient tout within our Association. Finally, I would like to offer a special thank you to Brad Gover (NRC), our Secretary in the past two years, who has chosen not to seek re-election due to other commitments. Chantal Laroche (University of Ottawa), who for years has been assisting our Editor-in-Chief in the publication of French issues of Canadian Acoustics and other matters, has been elected as our new Secretary at the last Annual General Meeting. As a close collaborator of Chantal over the years, I can attest to her great organizational skills and dedication in all that she undertakes.

Christian Giguère
CAA President

juste de terminer un mandat de six ans au sein du conseil d'administration et fourni une aide inestimable par son point de vue de fournisseur d'équipement acoustique. La bonne nouvelle est que Rich demeurera l'agent de publicité pour la revue l'Acoustique canadienne. Du même coup, j'en profite pour souhaiter la bienvenue à notre nouvelle directrice élue au conseil d'administration, Kathy Pichora-Fuller (University of Toronto Mississauga), qui possède un long historique au sein de notre Association. Enfin, je voudrais offrir un merci bien spécial à Brad Gover (CNRC), notre secrétaire durant les deux dernières années, qui a choisi de ne pas briguer un nouveau mandat en raison d'autres engagements. Chantal Laroche (Université d'Ottawa), qui depuis plusieurs années aide notre rédacteur en chef à la publication de l'Acoustique canadienne, tout particulièrement pour les numéros en français, a été élue comme nouvelle secrétaire à la dernière assemblée générale annuelle. En tant que proche collaborateur de Chantal au fil des ans, je peux témoigner de sa grande capacité d'organisation et de son grand dévouement dans tout ce qu'elle entreprend.

Christian Giguère
Président de l'ACA

# VERTICAL SOUND LOCALIZATION IN LEFT, MEDIAN AND RIGHT LATERAL PLANES

**Christian Giguère, Rosanne Lavallée, Julie Plourde and Véronique Vaillancourt**
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## ABSTRACT

A few studies have reported better auditory localization under binaural listening for sounds presented from the left side of midline compared to the right. That asymmetry was attributed to a superior ability to resolve front/back confusions in the left hemifield. This research further investigated asymmetric effects in an experiment assessing vertical localization in three lateral planes perpendicular to the interaural axis (median, left and right). Eleven sources spaced at 18-deg intervals were arrayed around the upper half of the cone-of-confusion intersection in each plane. Subjects (15 males, 9 females) were required to identify the direction of incidence of a 250-ms band-limited white noise stimulus (250-8000 Hz). Statistical analyses performed on the proportion of correct responses and on three different angular error measures did not uncover any significant effect in performance for sources on the left versus right side of subjects. However, significant gender differences favoring male subjects were found for the variable and total error measures. This finding may be a purely physical effect due to the smaller size of female ears on average or related to cognitive effects. Results must be viewed in light of the wide distribution of response patterns from subject to subject; while most responded symmetrically and over the entire localization array, some had distinctive asymmetrical behaviors and/or systematic response biases in specific sectors of the localization array.

## SOMMAIRE

Quelques études ont rapporté une meilleure capacité de localisation lors de l'écoute binaurale pour des sons présentés à la gauche, comparativement à la droite, de la ligne médiane. Cette asymétrie a été attribuée à une capacité supérieure à résoudre les confusions avant/arrière dans le demi-champ gauche. Cette étude a examiné davantage de tels effets asymétriques lors d'une expérience portant sur la localisation verticale dans trois plans latéraux perpendiculaires à l'axe interaural (médian, gauche et droit). Onze sources sonores séparées de 18 degrés étaient réparties sur la moitié supérieure de l'intersection entre le cône de confusion de chaque plan. Les participants (15 hommes et 9 femmes) devaient identifier la provenance d'un stimulus constitué d'une bande limitée de bruit blanc (250-8000 Hz) de 250 msec. Des analyses statistiques effectuées sur la proportion de bonnes réponses ainsi que sur trois différentes mesures d'erreur angulaire n'ont pas révélé de différence significative dans les performances de localisation pour les sources à la droite et à la gauche des participants. Par contre, un effet significatif du genre favorisant les hommes a été noté pour les mesures d'erreur variable et d'erreur totale. Ce phénomène pourrait être relié au fait que les oreilles des femmes sont plus petites que celles des hommes en moyenne ou indiquer des différences cognitives. Les résultats doivent être interprétés avec prudence étant donné l'étendue interindividuelle importante de la distribution des patrons de réponse. Quoique la plupart des participants ont répondu symétriquement et sur toute l'étendue de l'arc de localisation, d'autres présentaient des réponses distinctivement asymétriques et/ou teintées d'un biais systématique pour certains secteurs de l'arc de localisation.

## 1. INTRODUCTION

It is generally recognized that accurate sound localization in three-dimensional space relies on both binaural and monaural cues. While localization in the horizontal or azimuthal plane is based mainly on binaural cues, such as the interaural time and level differences, localization in the vertical mid-sagittal plane or judgment of sound elevation is primarily dependent on monaural spectral cues from the filtering effects of the pinna, head and body (Hebrank and Wright, 1974; Asano et al., 1990; Blauert, 1997). Spectral cues have also been shown to help resolve the various locations on a cone-of-confusion, positions characterized by equivalent interaural differences, thereby reducing front/back and up/down discrimination errors in lateral planes parallel to the mid-sagittal plane (Morimoto and Aokata, 1984).

Animal studies have shown that the cerebral hemisphere contralateral to a sound source is more predominantly activated in response to the source than the ipsilateral hemisphere, suggesting that the left and right hemispheres may be important in localizing sounds in the right and left hemifields, respectively (Neff and Casseday, 1977; Jenkins and Masterton, 1982; Jenkins and Merzenich, 1984). Asymmetrical activation of the brain to sound stimuli has also been reported in several human studies (Reite et al., 1981; Pantev et al., 1986; 1998; Tiihonen et al., 1989; Makela et al., 1993; Woldorff et al, 1999; Kaiser et al., 2000; Kaiser and Lutzenberger, 2001; Richter et al., 2009). Moreover, hemispheric differences in auditory processing exist in many species, such as the rat (Fitch et al., 1993) and Mongolian gerbil (Wetzel et al., 1998) as well as in humans (Hellige, 1990; Fitch et al., 1997; Patterson et al., 2002). In a review of evidence, Zatorre et al. (2002) argue that the left hemisphere is better at resolving temporal information necessary for speech understanding whereas the right cortical areas are better at analyzing spectral information critical to music perception. The right hemisphere's greater involvement in spatial hearing is also supported by findings of many electrophysiological, magnetoencephalograpy, lesion and imaging studies (Altman et al., 1979; Ruff et al., 1981; Bisiach et al., 1984; Griffiths et al., 1998; Tanaka et al, 1999; Weeks et al., 1999; Itoh et al., 2000; Kaiser et al., 2000; Palomäki et al., 2000; Kaiser & Lutzenberger, 2001; Zatorre and Penhune, 2001; Ducommun et al., 2002, 2004; Fujiki et al., 2002; Lewald et al., 2002; Arnott et al., 2004; Krumbholz et al., 2005; DeSantis et al., 2007; Spierer et al., 2009). Fujiki et al. (2002), for example, investigated auditory space representation in the human auditory cortex to changes in the azimuth and elevation of a virtual sound source. Their findings suggest that sound azimuth is analyzed mainly in the cortex contralateral to the sound source, whereas spectral cues critical to judgments of elevation are analyzed more extensively by the right hemisphere.

Given a dominant activation in the hemisphere contralateral to the stimulated ear, a right-hemisphere specialization for spectral processing, and the importance of spectral information in spatial hearing, a left-ear advantage can be hypothesized in the ability of localize sounds. Although a left/right (L/R) asymmetry has not been demonstrated in all human studies on normal subjects or those with brain lesions (Sanchez-Longo et al., 1957; Sanchez-Longo and Forster, 1958; Fritze et al., 1973; Oldfield and Parker, 1984; Poirier et al., 1993), a right-hemisphere dominance in the analysis of spectral information has been reported in some studies, as demonstrated by a greater accuracy in localizing sounds emanating from the left hemifield or when listening with the left ear in some situations (Ivarsson et al., 1980; Duhamel et al., 1986; Butler, 1994; Burke, et al., 1994; Abel et al., 1999; 2000; Savel, 2009).

Ivarsson et al. (1980), for example, tested vertical localization of band-pass noise presented binaurally or monaurally over four loudspeakers placed in the mid-sagittal plane at 11° intervals. A foam plug (experiment 1) or masking noise (experiment 2) was used to block the left or right ear in the monaural conditions. In both experiments, performance was better in the binaural listening condition than in the monaural conditions. In the first experiment carried out with 9 subjects, left-ear monaural performance was better than the right ear despite the lack of statistical significance which could be attributed to the small number of subjects. In the second experiment with 15 subjects, mean performance was statistically higher when listening with the left ear than with the right ear. Furthermore, when dividing the subjects into two groups, males and females, the L/R difference reached statistical significance only for the group of males. The greater ability to localize with the left ear was interpreted as evidence supporting the superiority of the right hemisphere for vertical sound localization.

Butler (1994) extended the Ivarsson study by assessing the ability to localize a high-pass noise originating from eight loudspeakers in the mid-sagittal plane in 10 subjects listening with the left ear, with the right ear and with both ears. An E-A-R insert and ear muff were used to block one ear in the monaural conditions. In contrast to the Ivarsson et al. (1980) study, inactive loudspeakers were also positioned to cover a region extending to ± 90° in the horizontal plane and from -45° to +60° in the vertical plane. Given the tendency to perceive sounds toward the listening ear in monaural conditions, this experimental setup allowed quantification of the magnitude of localization errors in both vertical and horizontal dimensions. In agreement with previous studies, all subjects exhibited greater localization accuracy when listening binaurally. Moreover, sound localization was significantly more accurate and the perceived displacement from midline was less when listening with the left ear than with the right ear. Such a left-ear advantage in monaural sound localization was interpreted as a right-hemisphere superiority in processing complex spectral information.

Following up on these studies, Burke et al. (1994) investigated asymmetry under binaural listening conditions, hypothesizing that if such an L/R asymmetry exists, sounds emanating from the left hemifield would be more accurately localized by binaural listeners. Sound localization was assessed in 20 right-handed and 20 left-handed subjects using broadband noise originating from 104 loudspeakers equally spaced in the horizontal and vertical dimensions over the left or right side of the subjects. When analyzing the results with respect to the horizontal coordinates, a significantly greater accuracy in localization was found when sources were placed in the left hemifield, independently of the subjects' handedness. The L/R asymmetry was no longer significant after compensating for front/back reversal errors. Since spectral cues provide critical information for discriminating sounds from the front and back, the hemifield effect in judging the horizontal coordinates of sound sources and the lack thereof after compensating for front/back reversals were attributed to a superiority of the right hemisphere in processing spectral cues. However, no main effect of hemifield was noted when localization judgments were analyzed with respect to the vertical coordinates, for which spectral cues are also expected to be critically important. This conflicting finding was attributed to the nature of the localization task in which interaural time and level differences provided adequate cues to discriminate along the vertical dimension in their coordinate system for sources off the mid-sagittal plane, thus making vertical judgments insensitive to spectral cues. This highlights the importance of the array design, response set and choice of head-related coordinate system in analyzing sound localization data (Searle et al., 1976; Perrett and Noble, 1995).

Abel et al. (1999) assessed the ability to localize three stimuli (one-third octave bands centered at 0.5 and 4 kHz, and broadband noise) in the horizontal plane (over 360°) in 16 subjects. The broadband noise was easiest to localize while the 0.5 kHz band yielded the lowest accuracy. However, a left-advantage was evident for the low-frequency stimulus, which was largely due to a higher incidence of front/back reversals on the right side. This L/R asymmetry was later found to be evident until the fifth decade of life (Abel et al., 2000).

The sound localization studies reviewed above suggest that the processing of spectral information is better performed by the right hemisphere (left-ear advantage). However, a recent study investigating gender-specific hemispheric asymmetry in monaural localization in the vertical dimension portrays a somewhat more complex situation. Lewald (2004) assessed sound localization of a high-frequency band-pass filtered noise over 31 loudspeakers in the mid-sagittal plane for 22 right-handed males and 22 right-handed females. A monaural left-ear advantage was noted in the female group; however, a monaural right-ear advantage prevailed in the male group. When combining the two groups, no asymmetry was found, a finding consistent with other studies failing to show a L/R asymmetry in sound localization, but contrary to the Ivarsson et al. (1980) study in which a significant left-ear advantage was found in males.

Previous studies examining possible L/R asymmetry in sound localization focused on the traditional spherical coordinate system to describe sound source positions and localization responses (azimuth angle from -180 to 180° in the horizontal plane and elevation angle from -90 to 90° in vertical planes intersecting the mid-sagittal plane). However, as found in Burke et al. (1994), interaural time and level difference cues are available to discriminate among sources placed in vertical planes intersecting the mid-sagittal plane, not only spectral cues (Perrett and Noble, 1995), and this reduces the sensitivity to detect L/R asymmetries if such an asymmetry is based on spectral processing. Instead, a head-related coordinate system based on the cone-of-confusion is warranted, such as the interaural-polar-axis system (Morimoto and Aokata 1984; Middlebrooks et al., 1989; Morimoto et al. 2003). In this system (Figure 1), lateral angle $\alpha$ subtended from the vertical axis, describes the cone-of-confusion surface on the left ($-90° \leq \alpha < 0°$) or right ($0° < \alpha \leq 90°$) side of the mid-sagittal plane (defined as $\alpha = 0°$), whereas vertical angle $\beta$ determines the angular position of the sound source on the cone-of-confusion in the plane perpendicular to the interaural axis and intersecting the sound source ($-180° \leq \beta \leq 180°$ with front defined as $\beta = 0°$). Using this system, Morimoto and Aokata (1984) showed that sound localization can be explained by two mutually independent cues: binaural difference cues for resolving angle $\alpha$, and spectral cues for angle $\beta$. Abel et al. (1999; 2000) exploited this coordinate system in rescoring their data. However, the range of $\beta$ angle positions was restricted to two, front ($\beta$=0°) and back ($\beta$=180°), thereby limiting analysis of possible left/right asymmetries to front/back discrimination, instead of fine vertical localization perception.

The objective of this study is to determine if a L/R asymmetry exists when listeners are presented with many stimulus and response options for the vertical angle $\beta$, while lateral angle $\alpha$ remains fixed and the source array placed on the left or right side of subjects. A binaural open ear localization paradigm is used to reflect natural listening and avoid complications in interpreting monaural sound localization data (Wightman and Kistler, 1997). Based on previous findings, an asymmetry may be anticipated, with a greater accuracy localizing sounds in the left side, thereby supporting evidence of right-hemisphere dominance in the analysis of spatial information. Should an asymmetry exist, it must also be taken into consideration in the design and administration of sound localization tests for clinical and functional hearing assessments.

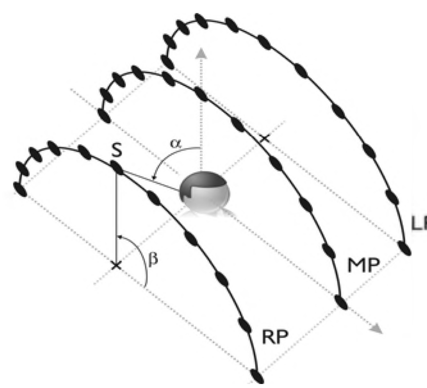


**Figure 1.** Interaural-polar-axis head-related coordinate system [adapted from Morimoto et al., 2003] ($\alpha$ = lateral angle between the source S and the vertical axis; $\beta$ = vertical angle between the source S and the horizontal plane in the direction perpendicular to the interaural axis). The three lateral positions of the 11-speaker localization array used in this study are also shown (RP = Right plane; MP = Median plane; LP = left plane).

## 2. METHOD AND MATERIALS

### 2.1 Subjects

Twenty-four subjects (15 men and 9 women) between 19 and 29 years old (average age = 24) participated in this study. All but three subjects were right-handed. In addition to having normal hearing bilaterally, as defined by pure tone thresholds no greater than 20 dB HL at 250, 500, 1000, 2000, 4000 and 8000 Hz, subjects had to meet the following inclusion criteria: (1) normal otoscopic evaluation; (2) normal tympanograms; (3) symmetrical hearing, defined as an ear-difference in thresholds no greater than 10 dB at any audiometric frequency tested; and (4) symmetrical vision, defined as a difference no greater than one line on the Snellen Chart. This last criterion ensured that visual acuity was similar for both lateral fields and would not be a confounding factor in assessing possible L/R asymmetries in sound localization.

### 2.2 Experimental Design

Sound localization was assessed using 11 miniature loudspeakers (Realistic Minimus 3.5) matched in frequency response within ± 2.5 dB for third-octave bands from 100 to 12000 Hz and mounted on a semi-circular arc with a radius of 1 m. The sources were separated by 18° along the arc to span a range of 180° in angular space. The localization arc was positioned vertically in three lateral planes perpendicular to the interaural axis, as shown in Figure 1. Thus, in each plane, the sound sources were distributed around the cone-of-confusion at vertical angles β of 0° (front), 18°, 36°, 54°, 72°, 90° (above), 108°, 126°, 144°, 162 ° and 180° (back) in the upper hemisphere. In the median sagittal plane condition (MP), the arc was placed directly above the subjects (lateral angle $\alpha = 0°$). In the left lateral plane condition (LP), the arc was positioned to the left, 58 cm from the subjects' head, at a lateral angle α of -30° from the vertical axis, whereas it was positioned at the same distance to the right at a lateral angle α of 30° in the right lateral plane condition (RP).

The experiment was carried out in a 5.6 m × 2.9 m × 2.0 m audiometric room. Subjects were seated on an adjustable stool, about 87.5 cm from the floor, ensuring that the ears were at the same height as the boundary sources on the semi-circular arc ($\beta=0°$ in front and $\beta=180°$ at the back). To minimize L/R asymmetric room acoustic effects and to facilitate administration of the experimental conditions, the sound localization array remained fixed in space in the center of the room. The stool, rather than the arc, was moved from one experimental condition to the next. In the MP condition, the stool stood in the center of the room with the localization array directly above the subjects' head. In the LP condition, the stool and subjects were moved by 58 cm to the right along the interaural axis. In the RP condition, the stool and array were in the same position in the space as the LP condition, but the subjects were rotated by 180°.

The stimulus to be localized was a 250-msec sample of band-limited white noise (250-8000 Hz) with a 25-ms rise and fall time presented at a comfortable level (60 dB SPL). While important cues to vertical sound localization exist at frequencies well above 8000 Hz (Hebrank and Wright, 1974; Shaw, 1997; King and Oldfield, 1997; Blauert, 1997), a more restricted stimulus bandwidth was used in this study to better reflect the functional localization abilities of human listeners to everyday sounds such as speech, warning signals or other environmental noises (Jelonek, 1991).

### 2.3 Procedure

Subjects received no formal training prior to the start of the experiment, other than listening without feedback to a sequence of a few trials to familiarize them with the data collection system. Each subject was tested under all three experimental conditions and testing order was counterbalanced between subjects to control for potential order effects. The stimulus was presented randomly 6 times from each of the 11 speakers, for a total of 66 trials in each listening condition. Prior to each trial, subjects were required to sit still and fixate a visual target placed straight ahead on the wall of the testing chamber. Head movements were not allowed during stimulus presentation. Following each presentation, subjects were required to identify the speaker through which the stimulus was thought to originate using a tactile screen displaying the response choice in the same semi-circular arrangement as the speaker array. A maximum response time of 10 seconds was allowed, after which there was a 2-second interval for reassuming the original head position before the next stimulus. Guessing was encouraged in case of uncertainty and no feedback was provided during testing.

### 2.4 Data Analysis

Sound localization was assessed using four measures: the proportion of correctly identified sound sources, and the three angular errors proposed by Rakerd and Hartmann (1985). The latter allow the identification and quantification of the types of localization errors committed. The first of these, the mean error, consists of the signed arithmetic average of the angular error in degrees over the 6 trials for a given stimulus source, thereby indicating the size and direction of any response bias or systematic error. A negative mean error represents a tendency to respond to a source positioned at a smaller vertical angle β than the actual target source (a bias towards the front), whereas a positive mean error indicates a tendency to respond at a larger vertical angle β (a bias towards the back). The second type of error, the variable error, is the standard deviation of the angular errors for a given source target and represents the consistency of subject responses once response bias is eliminated. Finally, the third type of error, the total error, is the root mean square of angular errors for a given source target and represents the global error in localization without regards to the direction of the error.

The four performance measures were calculated separately for each subject, source angle β and localization plane. Each measure was submitted to a mixed design ANOVA, with two repeated-measures variables [localization plane (3 levels) and target angle β (11 levels)] and one between-group variable (gender).

## 3. RESULTS

### 3.1 Response Patterns

Inspection of the confusion matrices revealed that response patterns varied greatly among the 24 subjects. About half the subjects (ten males, three females) responded fairly uniformly over the entire array, without a clear evidence of bias. Others, including the majority of females, responded preferentially in specific sectors of the vertical array, often front/above (four males, four females), but sometimes frontally (one female) or in different sectors in the different localization planes (one male, one female). The response patterns for females clearly showed more variability and a greater occurrence of front/back confusions (in 23.6% trials) than males (10.8% trials), as shown in Table 1. Finally, most subjects (ten males, five females) had similar response patterns in the two lateral planes LP and RP; however, distinct asymmetrical behaviors (difference ≥10% in identification accuracy between the two lateral planes) was evident among the other subjects favoring LP (three males; two females) or RP (two males, two females).

**Table 1.** Percentage of front/back confusions by gender and plane.

| Plane | Male | Female | Total |
|---|---|---|---|
| Right | 12.3 | 24.8 | 17.0 |
| Median | 12.3 | 19.8 | 15.1 |
| Left | 7.7 | 26.1 | 14.6 |
| All planes | 10.8 | 23.6 | 15.6 |

### 3.2 Performance Measures

Figure 2 presents the localization data averaged over all subjects by vertical source angle for each of the four performance measures (percent correct and three angular errors) and three lateral planes. Figure 3 presents the summary localization data averaged over vertical source angle by gender.

3.2.1 Proportion of correct responses

The repeated-measures ANOVA revealed a significant main effect of target angle β on the subjects' identification accuracy in localizing sources [$F(10,220) = 3.756$, $p < 0.001$]. No significant main effect of localization plane [$F(2,44) = 1.043$, $p = 0.361$] or gender [$F(1,22) = 2.843$, $p = 0.106$], or interaction among factors were found at the 0.05 confidence level.

As shown in Figure 2, the proportion of correct responses was similar overall in all three planes and shows the same pattern as a function of target angle. Averaged across the three planes, target sources were more accurately identified in the front sector (range = 0.30 to 0.36) than the above (range = 0.22 to 0.30) and back (range = 0.16-0.21, with the exception of target angle β = 180° with a 0.30 accuracy) sectors. Repeated within-subjects contrasts, used to compare neighboring β angles, showed a significant difference in localization between β pairs 108-126° and 162-180°.

3.2.2 Mean error

Again, the repeated-measures ANOVA revealed a significant main effect of target angle [$F(10,220) = 46.164$, $p < 0.001$], but no significant main effect of localization plane [$F(2,44) = 0.535$, $p = 0.589$] or gender [$F(1,22) = 2.324$, $p = 0.142$], or interaction among factors at the 0.05 confidence level. As shown in Figure 2, the mean error was near zero (no response bias) for target angle β around 54-72°, but systematically increased in absolute terms in all three planes towards the two boundary sources (β = 0 and 180°). Target angles in the front sector were associated with positive mean errors, indicating a response bias towards the back or overhead; whereas angles within the above and back

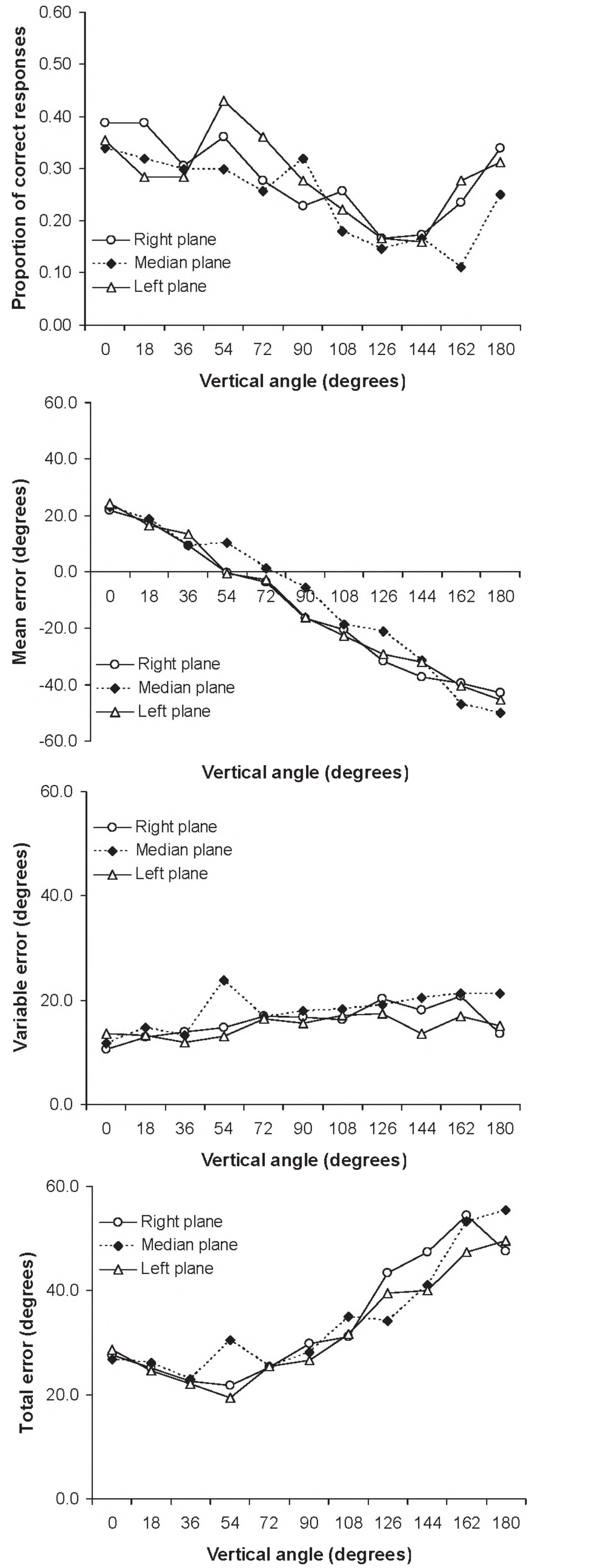


**Figure 2.** Localization performance by lateral plane (RP, MP, LP) as a function of the vertical source angle. Data averaged across all subjects. Results are shown for the proportion of correct responses and the three error types.

sectors were generally associated with negative mean errors, indicating a bias towards the front. Repeated within-subjects contrasts revealed significant differences between all pairs of adjacent angles β (0-18°, 18-36°, 36-54°, 54-72°, 72-90°, 90-108°, 108-126°, 126-144° and 144-162°), with the exception of the most backward pair (162-180°).

### 3.2.3 Variable error

The repeated-measures ANOVA performed on the variable error revealed a significant main effect of target angle [$F(10,220) = 4.438$, $p < 0.001$], localization plane [$F(2,44) = 6.008$, $p = 0.005$] and gender [$F(1,22) = 4.289$, $p = 0.050$], but no significant interactions among factors at the 0.05 confidence level. The main effect of angle is shown in Figure 2, where the variable error tends to increase slightly in all three planes from front to back sources. Repeated within-subjects contrasts found a significant difference between only two successive target angles: 36 and 54°.

The main effects of localization plane and gender are illustrated in Figure 3. Tests of within-subjects contrasts revealed a significant difference in localization plane between MP and both RP ($p = 0.045$) and LP ($p = 0.002$), with a greater variable error committed in MP (18.1°) than RP (15.9°) or LP (14.9°). There was no significant difference between the two lateral conditions RP and LP ($p = 0.248$). Finally, male subjects performed better (smaller variable error) than female subjects by 3.1° over the three localization planes (15.1 versus 18.2°).

### 3.2.4 Total error

The repeated-measures ANOVA performed on the total error revealed a significant main effect of target angle [$F(10,220) = 10.013$, $p < 0.001$] and gender [$F(1,22) = 9.512$, $p = 0.005$], but also a significant interaction between localization plane and gender [$F(2,44) = 3.451$, $p = 0.041$]. No significant main effect of localization plane [$F(2, 44) = 0.134$, $p = 0.875$], or other interactions were found at a 0.05 confidence level. As illustrated in Figure 2, there was a general increase in total error in all three planes with increasing target angle β. Averaged over the three planes, the error was smallest for angles in the front sector (range = 22.6 to 27.7°), followed by the above sector (range = 25.4 to 32.6°) and the back sector (range = 39.0 to 51.7°) where it was the largest. Repeated within-subjects contrasts on pairs of successive source angles β showed the following pairs to be significantly different: 18-36°, 90-108°, 108-126° and 144-162°, with a tendency of larger total errors for larger angles, except for the first pair.

Males (28.4°) performed significantly better than females (42.4°) on the total error measure, as shown in Figure 3. Finally, tests of within-subjects contrasts demonstrated an interaction between gender and localization plane, but only when MP is compared to LP ($p=0.01$). This interaction is clearly noted in Figure 3. Although males performed better in LP (24.7°) than MP (31.9°), female exhibited greater total errors in LP (44.1°) than MP (38.6°).

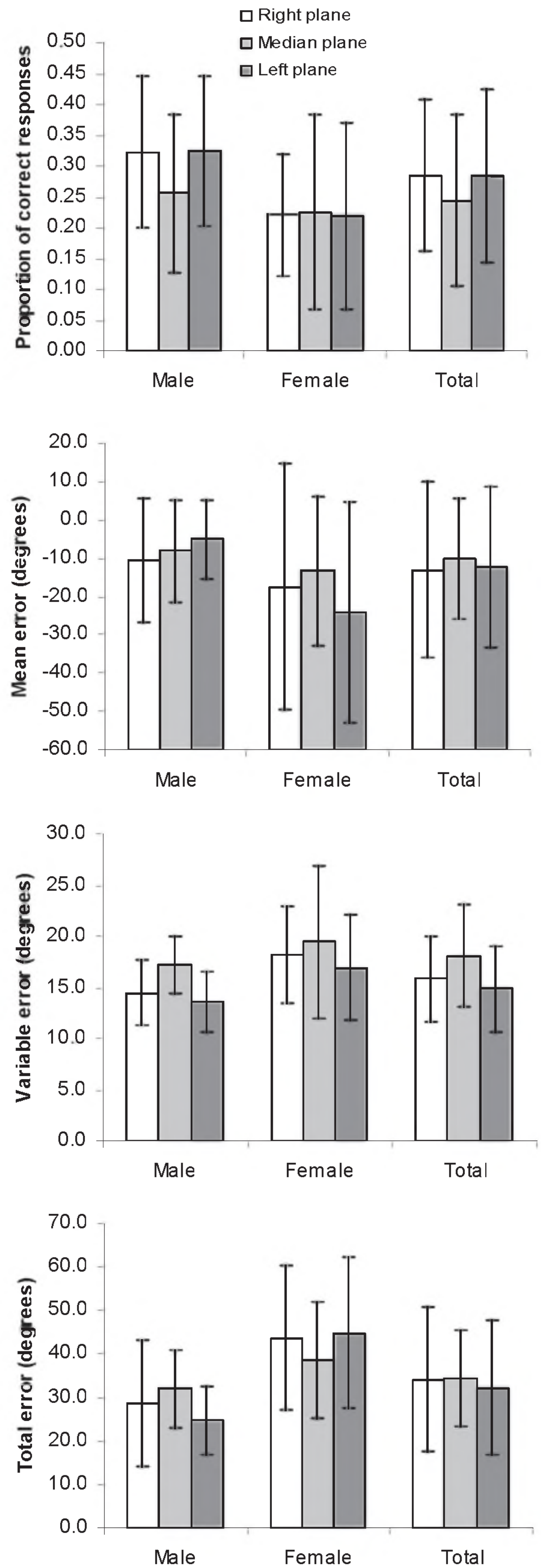


**Figure 3.** Localization performance by gender and lateral plane (RP, MP, LP). Data average across vertical source angles. Error bars represent ± one standard deviation. Results are shown for the proportion of correct responses and the three error types.

## 4. DISCUSSION

The main objective of this study was to further explore a possible asymmetry in vertical sound localization under binaural listening. A few studies (Burke et al. 1994; Abel et al., 1999; 2000) had indicated better localization for sources on the left side, particularly with respect to front/back perception, and that the asymmetry was likely related to the processing of spectral cues. Other studies had shown asymmetrical localization abilities in the median plane under left or right monaural conditions (Ivarsson et al., 1980; Butler, 1994; Lewald, 2004), possibly interacting with gender. However, previous studies were generally limited to mid-sagittal plane localization or offered confounding interaural cues that could be used to judge elevation, in addition to spectral cues. Instead, this study assessed asymmetry using a semi-circular arc positioned perpendicularly to the interaural axis, in the median plane and in left and right lateral planes. Sound sources were arrayed around the upper half of the cone-of-confusion intersection in each plane (Figure 1), thus minimizing the confounding effects of interaural cues.

The study design yielded a fairly challenging localization task, given the short duration (250 ms) and band-limited white noise stimuli used (250-8000 Hz). As shown in Figure 2, the proportion of correct responses varied from 0.11 to 0.43 (chance = 0.09) across conditions, and there were relatively large localization errors. The mean error showed a general response bias toward a neutral direction of approximately 60° in vertical elevation. This pattern was shown in all three localization planes. Mean error was largest for the boundary in the front and back, where it dominated the total error. Such edge effects were expected and had been previously noted in other studies (e.g. Rakerd and Hartmann, 1985). In contrast, mean error was smaller for source positions above, where variable error was the dominant component. The latter, while slightly increasing from front to back, showed much less variation with source positions than mean error. Overall, the size of total errors was fairly large compared to other studies (Burke et al., 1994; Makous and Middlebrooks, 1990; King and Oldfield, 1997; Best et al., 2005). Typically, a wider stimulus bandwidth is used and front/back reversals are often compensated for or screened out from the results. In this study, front/back reversal errors, which occurred in about 15.6% of trials, were not compensated for since they appear to reflect a class of errors indistinguishable from other elevation errors (Morimoto and Aokata, 1984). Best et al. found a similar proportion of reversal errors (16.4%) for speech stimuli low-pass filtered at 8000 Hz.

A main outcome of this study was that repeated-measures ANOVAs performed on the proportion of correct responses and on three different angular error measures (mean, variable, total) did not uncover any significant difference in performance for sources in the left versus right planes. Indeed, localization plane was not a main effect or an interaction effect for the proportion of correct responses and the mean error measure. While plane was a main effect for the variable error, it was the result of a slightly higher error in the median plane compared with the left or right lateral planes, not between left and right planes. Likewise, a significant interaction involving localization plane was found for the total error measure, but it only involved the median plane compared with the left plane; males had smaller total error in the left plane than the median plane and the converse for females. Observation of the pattern of errors across source angles in Figure 3 also did not show any important effect involving left versus right planes. Thus, there is little evidence in this study in support of asymmetric vertical sound localization abilities for sources positioned laterally on the left or right sides. It is important to realize, however, that there were large intersubject variations in the data and, as pointed out earlier in Section 3.1, some subjects showed distinct L/R asymmetrical behaviors that are not well accounted for in group data. Butler (1994) also observed distinct asymmetrical response patterns across subjects for vertical elevation under monaural listening conditions.

While care was taken to minimize reflections and provide the most symmetrical layout possible, the influence of asymmetrical room reflections in the audiometric testing room cannot be fully discounted. It was already noted that distinct asymmetrical behavior was found in some subjects, but not in others, despite listening to the same sound field. This, together with the main finding of a null hypothesis for left versus right localization plane, makes it unlikely that reflections contributed adversely to the study outcome. Given the study design and response variability, a mean difference in total error of about 7° (or slightly less than half the source angular spacing) was detectable between localization planes at the 95% confidence interval, whereas a mean difference of less than 2° was observed between left and right planes.

Gender, however, appeared as a significant main or interaction factor for several performance measures in this study. Gender was a main effect for the variable and total error measures, and in both cases males showed significantly less error than females in all three localization planes (Figure 3). Comparative data on gender differences for vertical sound localization is limited. Interestingly, Lewald (2004) found a trend for males to be more precise (less variable) and show less total angular error in vertical localization in the mid-sagittal plane under binaural listening conditions. Under monaural listening conditions, a significant gender difference favoring males was found when listening to the right ear. Ivarsson et al. (1980) did not find gender differences under binaural listening conditions, but their data under monaural masking also showed a male advantage. In contrast to Lewald (2004), however, the male advantage was found for the left ear, instead of the right ear.

Concerning the origin of gender differences, we can hypothesize as in Best et al. (2005) that the generally smaller size of the outer ears of females is such that important spectral features for vertical localization are encoded at higher frequencies than for males on average. Indeed, Middlebrooks (1999) found that differences in directional transfer functions between subjects could be predicted by physical attributes, particularly pinna cavity height and head width, and that the spectral features of directional transfer functions lay at higher frequencies in females than in males. Thus, poorer performance found for band-limited stimuli for females could be a purely physical effect. Gender differences have also been reported for sound localization in the frontal horizontal plane. For example, using low-frequency noise bursts, Savel (2009) reported a gender difference in sound localization in 50 adults with normal hearing, with better performance in males. A left-hemifield advantage was also noted, which interacted with handedness and gender, being more strongly observed in right-handed males.

Cross-gender differences in performance could also be explained by differences in cognitive abilities related to the structural organization of male and female brains (Cahill, 2006), with men displaying superior visuospatial abilities (see Becker et al., 2008 for a review on sex differences in brain and behavior). A male advantage in spatial hearing abilities has also been reported (Lewald, 2004; Neuhoff et al., 2009; Simon-Dack et al., 2009; Zündorfz et al. 2011). For example, in an investigation of sex differences in auditory spatial localization by Zündorfz et al. (2011), right-handed subjects with normal hearing were required to localize five environmental sounds (dog barking, baby crying, telephone ringing, man laughing and cuckoo clock) in a single source condition and in a multi-source condition simulating a "cocktail party situation". In the latter, subjects had to localize a target sound in the presence of multiple competing sound sources. Irrespective of the response modality used (verbal and manual), males outperformed females in the multi-source condition and results were attributed to sex differences in higher-order attentional mechanisms.

Vertical sound localization is highly dependent on the frequency content of the stimulus (Hebrank and Wright, 1974; Musicant and Butler, 1984; Blauert, 1997; Best et al., 2005) and the response choice provided to the subjects. In this study, a stimulus bandwidth limited to 8000 Hz was used to depict the functional localization abilities of human listeners to everyday sounds. Asymmetry and gender issues may play out differently in applications for which an extended stimulus frequency range can be made available, such as in the design of audio displays (King and Oldfield, 1997). Best et al. (2005) showed that human listeners are much better at vertical sound localization for speech stimuli low-pass filtered at 16000 Hz than at 8000 Hz, indicating an important role of high frequencies for speech localization. However, high frequencies may easily be masked in real environments or rendered inaudible due to hearing loss or hearing aid bandwidth limitations. Finally, stimuli were presented at the same level across sources in the current study; it is uncertain if the lack of rove might have provided overall level cues that would have fostered significant effects in localization performance, notable for gender differences. Until L/R asymmetrical effects and gender differences are more clearly understood, future studies need to pay particular attention to control for these factors in clinical applications.

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# CT STUDY OF ACOUSTIC SIGNAL PATHWAY THROUGH THE MIDDLE EAR OF THE SPERM WHALE (*PHYSETER MACROCEPHALUS*)

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## ABSTRACT

The ability of marine mammals to adapt to an underwater acoustic environment is a remarkable evolutionary achievement. Of particular interest is how the middle and inner ear structures are modified relative to those of terrestrial mammals. For the large whale species there are very few anatomical descriptions of the ear, in part because of the large and dense bony structures involved. Because the sperm whale (*Physeter macrocephalus*) is listed as an endangered species, legal fresh specimens are rare. However old dry specimens can be found and we are able to present here a study of the periotic-tympanic bone complex of the sperm whale, using high resolution computer tomography (CT) imaging. We discuss the marine adaptations of the middle and inner ear structures.

## SOMMAIRE

La capacité des mammifères marins de s'adapter à un environnement acoustique sous-marin est une réalisation évolutif remarquable. D'un intérêt particulier est de savoir comment l'anatomie de l'oreille moyenne et interne sont modifiés par rapport à ceux des mammifères terrestres. Pour les grandes espèces de baleines il y a très peu de descriptions anatomiques de l'oreille, en raison de la grandeur et densité des os impliquées. Parce que le cachalot (*Physeter macrocephalus*), est classé espèce menacée, les spécimens frais sont rares. Toutefois, nous sommes en mesure de présenter ici une étude du labyrinthe osseux temporelle du cachalot, en tomographie haute résolution. Nous discuterons les adaptations de l'anatomie de l'oreille moyenne et interne pour l'environment marin.

## 1 INTRODUCTION

Whales are a part of the mammalian order Cetacea, which is subdivided into two suborders, Odontoceti and Mysticeti. Otodontocetes are toothed whales of which the sperm whale (*Physeter macrocephalus*) is the largest. Figure 1 outlines its main characteristics. Sperm whales are particularly vocal mammals and have a highly developed echolocation ability that makes use of broadband click patterns (codas) that pulse through water to locate food, navigate, and socialize (*e.g.* Madsen *et al.* 2002; Rendell and Whitehead, 2003). Click patterns appear to vary according to the group composition and activity. Several different vocalization patterns have been identified: i) vocalization associated with diving and feeding (echolocation clicks, creaks, and trumpet) and ii) vocalization associated with socializing (chirrups and squeals). The importance of echolocation for socialization and survival in the limited visibility in the ocean depths, stresses the need for a highly developed auditory system that can effectively detect and interpret sounds conducted through water.

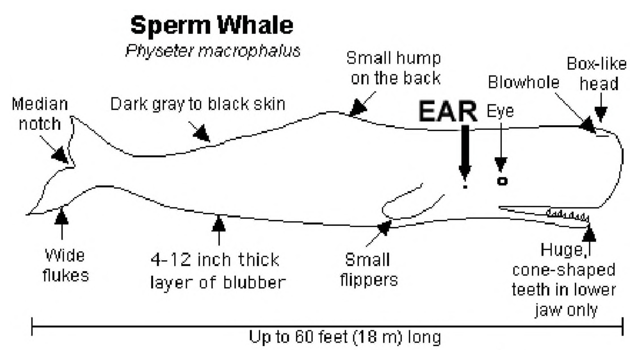


**Figure 1. General characteristics of *Physeter macrocephalus***

The auditory systems of whales are thus highly evolved and essentially act as the primary sensory organ of cetaceans. As the whale has evolved from a land to marine mammal, the audio-vestibular system has undergone evolutionary changes to adapt to this new environment (Nummela *et al.* 2004; 2007). Many of these anatomical evolutions have been described for various whale types, however, to date we have not found any descriptions of the middle ear anatomy of *Physeter macrocephalus*. There are CT scan studies in a number of whale species (e.g. Ketten,

1997) including fossil specimens (e.g. Stokstad, 2003) but few have examined the middle ear. There is much interest in the sound transmission within the bulbous nose of the sperm whales (e.g. Cranford, 1999; Mohl 2001), however there are no detailed descriptions or radiological studies of its middle ear as recently noted by Cranford et al. (2010). In the present study we examine the structure and function of the auditory and vestibular system of the sperm whale using high resolution CT imaging of two temporal bone specimens.

## 2 METHODS

### 2.1. Materials and DNA sequencing

Sperm whales are protected under the Endangered Species Act and the Marine Mammal Protection Act, thus fresh specimens are rare. We obtained old, left and right petrous temporal bones from the estate of whaling station manager. The transport and importation of the bones for academic study was approved by an officer of Environment Canada (Canadian Wildlife Service). To confirm species identification, DNA matching was carried out. Thus, DNA nucleic acid was extracted from bone powder samples and DNA sequencing information was used to ascertain accurate species information. This was carried out in the Ecology & Evolutionary Biology unit of University of Toronto, based at the Royal Ontario Museum. Ten sequences producing significant alignments were identified, with the closest match being *Physeter macrocephalus*.

### 2.2. CT Scanning

Computer tomography (CT) was used to identify the structural components of the bones. A General Electric (GE) 1.5 Tesla scanning system was used to examine the bones. The very dense nature of the specimens was a challenge but we could resolve 0.625 mm slices with a spatial image of 512 x 512 (approx. pixel size = 0.04mm). Using Advantage Workstation software, 3-D reformats were created from axial slices and differential bone densities were used to identify large structures housed within the dense bone. In this study the gross specimens and CT images were correlated with anatomy of the whale petrous temporal bone previously described in the literature, as well as in relation to more familiar human temporal bone structures.

## 3 RESULTS

Photographs of right and left temporal bone specimens of *Physeter macrocephalus* are shown in figure 2, with the periotic and tympanic bones of the T-P complex identified.

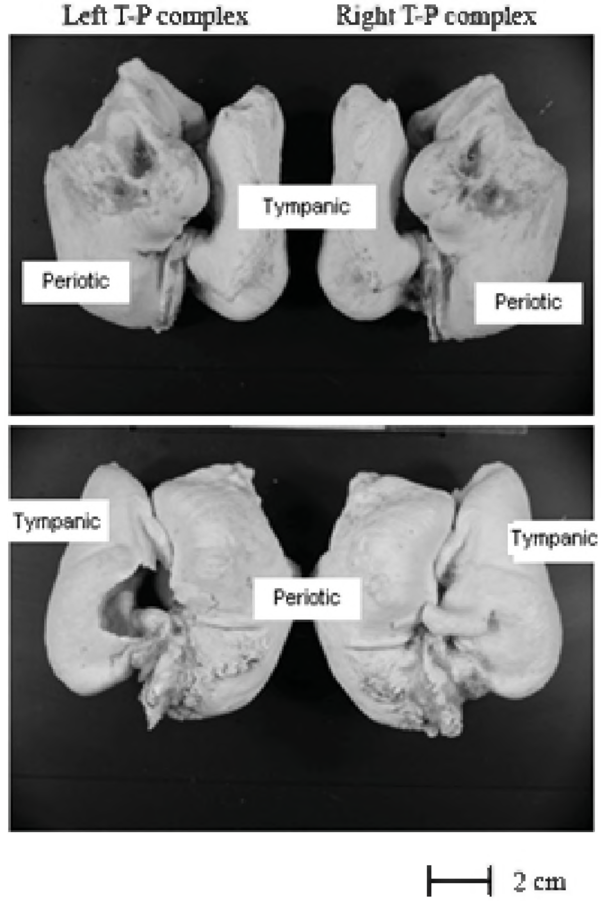


**Figure 2. Gross images of the left and right petrous temporal bones of a sperm whale (*physeter macrocephalus*). Upper panel: Medial view. Lower panel: Lateral view.**

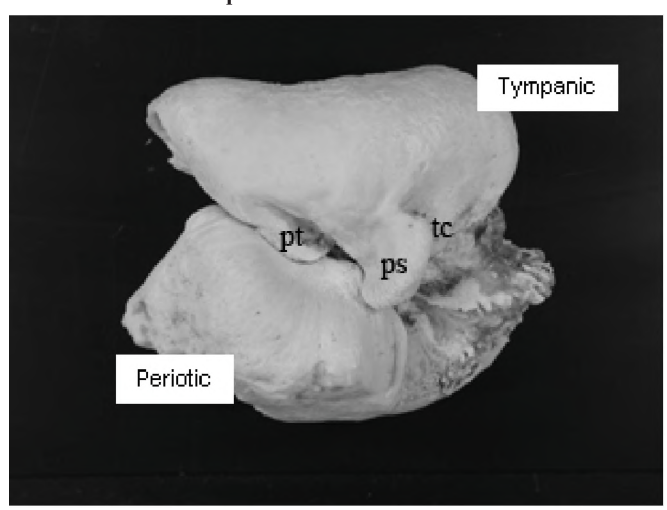


**Figure 3. Right temporal bone showing structures that link tympanic and periotic segments of the T-P complex. pt: processus tubarius; ps: processus sigmoideus; tc: tympanic conus.**

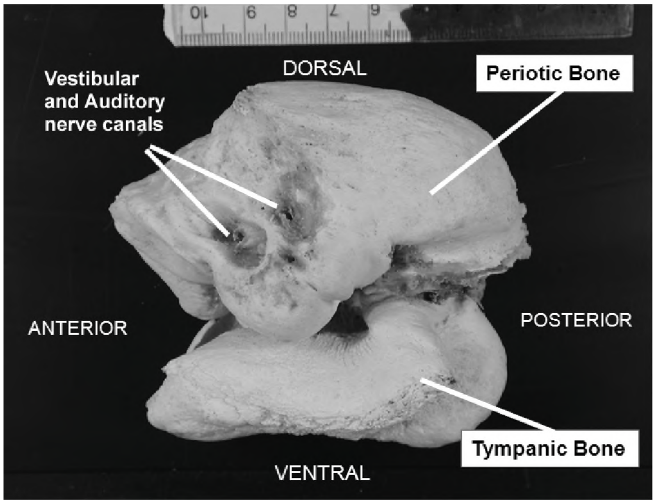


**Figure 4. Details the surface anatomy of the right temporal bone as viewed from the intra-cranial side, showing internal auditory and vestibular nerve canals. A mm ruler scale is shown.**

As shown in fig. 3, there is a connection between the tympanic and periotic bones via the processus tubarius (pt) anteriorly (an accessory ossicle) and more posterior there is the processus petrosus (not clearly visible). In between these processes lies the processus sigmoideus (ps), the very specific anatomical identifier for all whale species. Posterior to this is the tympanic conus, a calcified funnel that has a ligamentous attachment to the malleus. On the lateral aspect of the T-P complex (fig. 4), the large cochleo-vestibular nerve canal is observed.

CT imaging of the T-P complex from anterior to posterior is shown in figs. 5a-d. The tympanic plate (tp) is the thin portion of the ventrolateral wall of the tympanic bone which is connected via the processus gracilis (pg), a bony ridge, to the malleus (anterior portion of pg). The 'fixed' malleus is then connected to the oval window via the ossicular chain (not pictured here in continuity). The anterior (processus tubarius) and posterior (processus petrosus) T-P connections are again visualized in these serial CT sections (surface cuts through 3D images). The cochlea and the cochleo-vestibular nerve canal are noted within the periotic bone, as are the facial nerve canal and the cochlear aqueduct.

Using this CT imaging of the T-P complex, direct and indirect connections via the processus tubarius, processus petrosus, and processus gracillus could be identified. In addition the tympanic plate and tympanic conus (an evolutionary substitute for the tympanic membrane) were identified in their attachments to the malleus. Unfortunately our specimens were both lacking in a complete ossicular chain, and therefore we are unable to comment on the extent of fusion of the ossicular chain, or its connections to the periotic bulla. However, as shown in Figure 6 (particularly in the enlargement inset) we were able to identify the stapes superstructure positioned on the oval window.

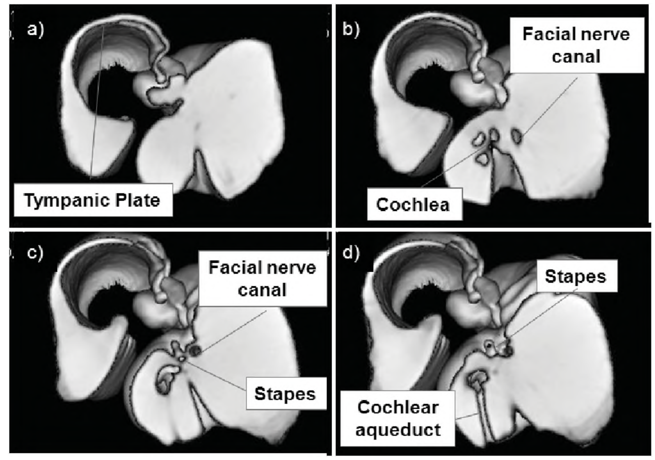


**Figure 5. CT sections of the left petrous temporal bone from anterior to posterior. The following features can be noted: In (a) connection of the malleus head via processus gracilis (bony ridge) and tympanic plate (thin portion of ventrolateral wall of tympanic bulla) to the processus tubarius (pt). In (b) connection of the T-P complex via processus petrosus (pp). Cochlea, cochlear canal, and facial nerve canal (VII) can be identified in the periotic bone. In (c) the stapes sits on the oval window, with the facial nerve superior. In (d) note the cochlear aqueduct posterior to cochlear canal.**

By making a 3-D reconstruction of the CT images we were able to picture (figure 7) the cochlea and its related structures deep within the dense periotic bone. The spiral cochlear structure is clearly seen as is the large cochleo-vestibular nerve canal, the cochlear aqueduct and facial nerve canal. Interestingly the cochlear apex points down with the round window posterior and medial to the oval window, as found in some other whale species (e.g. Ketten, 1997; Whitlow and Ketten, 2000).

With the CT image resolution of the present study we were able to identify the distinct grouping of vestibular organs (otoliths and semicircular canals). The size of the semicircular canals in cetaceans is considerably reduced compared with most other mammals, and this was the case in our sperm whale specimens. We found the diametric extent of the semi-circular canals to be approximately 10 mm. This is consistent with the small sized vestibular apparatus seen in other cetacean species and supports the evolutionary adaption of cetaceans to marine activity. The vestibular contribution of this organ is to provide gravity and linear acceleration cues, but with limited input for rotation and 3-D acceleration (e.g. Van Bergeijk, 1967; Ketten, 1997). There were no obvious aberrant structures identified in our petrous temporal bone specimens.

# 4 DISCUSSION

## 4.1 Transmission of acoustic signals to the tympano-periotic complex

One of the obvious evolutionary changes of the odontocete auditory system in the move from land to marine mammal is the loss of the external pinna and external auditory canal, with only a dimple or residual canal remaining that has no contact with the middle ear (Whitlow and Ketten, 2000). Sound is therefore transmitted to the middle ear via a large mandibular fat pad and is then received by the lateral wall of the temporal bone, known (and as described in this paper) as the tympano-periotic (T-P) complex. The T-P complex is composed of two connected bones: 1) the dorsal periotic bone, which encloses the inner ear and functionally connects to the brain via the vestibulo-cochlear nerve and 2) the ventral, bowl shaped, tympanic bone. This is often described as the tympanic bulla. It encloses the middle ear space and ossicular chain, and is in direct contact with the surrounding soft tissues. The T-P complex is isolated from the rest of the skull by surrounding air sinuses in a peri-bullar cavity and is suspended from the walls by ligamentous attachments (Ketten, 1997).

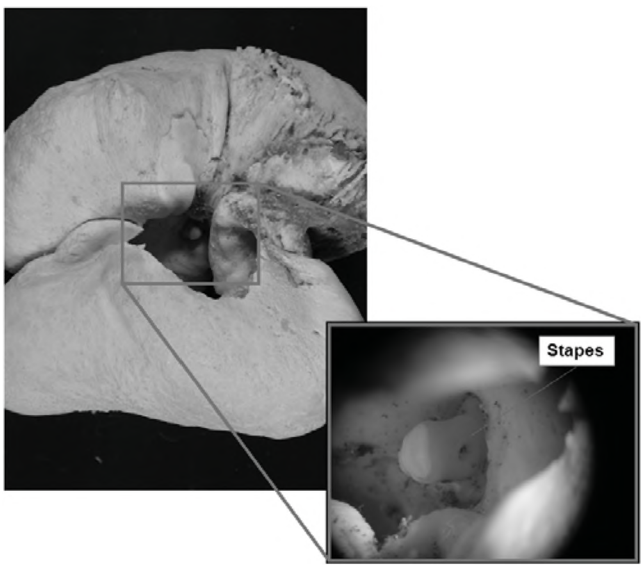


**Figure 6. Photographic imaging of the T-P complex with an enlargement showing the stapes present on the stapes footplate and oval window of the periotic bone.**

## 4.2 Ossicular transmission of acoustic signals from the tympanic plate to the cochlea

Once sound is transmitted via the mandibular fat pad, it vibrates the tympanic plate which is found on the ventrolateral wall of the tympanic bone. The acoustic signal is then transmitted by the ossicular chain, perhaps via the unusual impedance matching model proposed by Hemila et al. (1999). This transmission scheme suggests that increases in both signal amplitude and velocity occur as it travels from the tympanic plate, along the ossicular chain, to the oval window. The malleus is connected to the tympanic plate by an anterior bony ridge known as the processus gracilis which transmits sound vibration to the malleus-incus complex. The head of the malleus rests against the periotic bone while the other end connects to the incus and stapes. Vibration of the malleus causes the malleus to rotate around an axis that directs sound down the malleus-incus complex to the stapes supra-structure and footplate. The acoustic signal is then transmitted from the footplate across to the cochlea housed in the periotic bone (Hemila et al., 1999; Nummela et al., 2004). The cetacean cochlea has the same fundamental organization as other mammalian inner ears and is connected to the brain via the large cochleo-vestibular nerve.

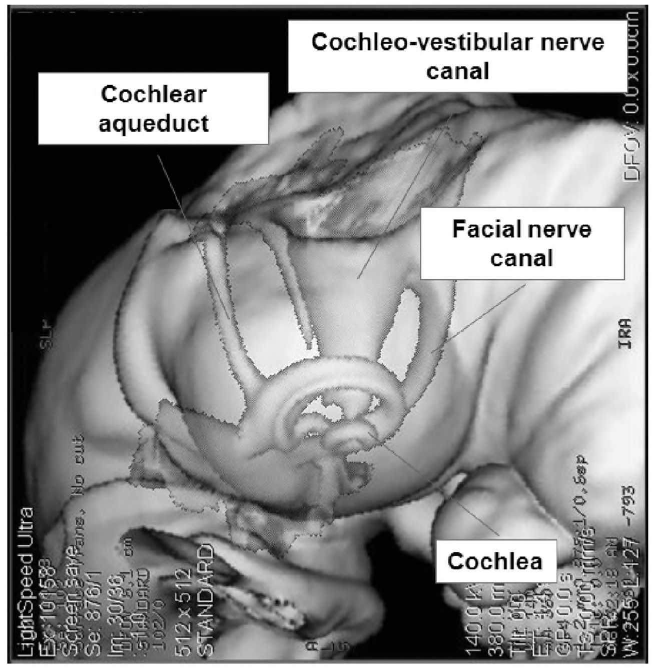


**Figure 7. Three dimensional CT reformat of the periotic bone showing the cochlea and associated cochlea-vestibular nerve canal. The cochlear aqueduct and facial nerve canal are clearly resolved.**

### 4.3 Vestibular function

The vestibular system of cetaceans has also undergone significant evolutionary changes with the conversion from land to marine mammal. These alterations result from changes in head movement, body movement, and gravitational forces. In an aquatic environment, cetaceans were freed from gravitational forces and increased their acrobatic abilities. In addition to this, their streamlined bodies, with fused cervical vertebrae and limited neck mobility, limited the need for reflex stabilization of the head. There is also likely a reduced need for vestibulo-ocular reflexes. Therefore, over time the size of the semi-circular canals of cetaceans has drastically decreased. In fact, their semi-circular canal size (corrected for body mass) is three times smaller than in other mammals. In addition to the reduced vestibular reflex requirements out lined above, it is also widely assumed that the small canal size acts to reduce the sensitivity of cetacean vestibular responses to high levels of uncompensated angular motion, thereby preventing overstimulation (Spoor et al. 2002).

## 5 SUMMARY

The anatomy of the middle ear has been well described for many cetacean species, however few specific descriptions exist for the sperm whale (*Physeter macrocephalus*). We were fortunate to acquire dry, left and right temporal bone specimens and confirm species by DNA analysis. Using modern CT scan technology we were able to identify and describe important anatomical features.

## ACKNOWLEDGEMENT

This study was supported in part by funding from the Masonic Foundation of Ontario.

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# NONLINEAR ACOUSTIC BEAM PROPAGATION MODELING IN DISSIPATIVE MEDIA

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## ABSTRACT

Accurate simulation of an intensive ultrasound beam requires taking nonlinear propagation effects into account. A notable example in the field of biomedical ultrasound where the effect of nonlinearity may play a significant role is the high intensity focused ultrasound (HIFU) as a non-invasive energy-based treatment modality. In this work, a 3D numerical model to simulate nonlinear propagation of continuous wave ultrasound beams in dissipative homogeneous tissue-like media is presented. The model implements a second-order operator splitting method in which the effects of diffraction, nonlinearity and attenuation are propagated over incremental steps. The model makes use of an arbitrary 3D source geometry definition method and a non axi-symmetric propagation scheme, which leads to a 3D solution to the resulting nonlinear ultrasound field. This work builds on methods developed by Tavakkoli *et al.* (1998) and Zemp *et al.* (2003) and offers an efficient way to calculate nonlinear field of continuous wave ultrasound sources. The proposed model is a particularly useful computational tool in carrying out simulations of high intensity focused ultrasound beams in soft tissue where the effects of nonlinearity, diffraction, and attenuation are important. The model was validated through comparisons with other established linear and nonlinear numerical models as well as published experimental data.

## RÉSUMÉ

La simulation précise d'un faisceau d'ultrasons intensive nécessite de prendre des effets de propagation non-linéaire en compte. Un exemple notable dans le domaine d'ultrasons biomédicale où l'effet de la non-linéarité peut jouer un rôle important est des ultrasons focalisés de haute intensité (HIFU) comme un modalité de traitement fondées sur l'énergie non-invasive. Dans ce travail, un modèle numérique 3D pour simuler la propagation non-linéaire des ultrasons à ondes continues dans un milieu dissipatif et homogène similaire au tissue est présenté. Le modèle met en œuvre une méthode de deuxième ordre d'opérateur dans lequel les effets de diffraction, la non-linéarité et de l'atténuation sont propagées de façon additive. Le modèle utilise une méthode arbitraire de définition de source géométrie 3D et un régime de propagation non-axisymétriques, ce qui conduit à une solution 3D au domaine d'ultrasons non-linéaire qui en résulte. Ce travail s'appuie sur des méthodes développées par Tavakkoli *et al.* (1998) et Zemp *et al.* (2003) qui offre un moyen efficace de calculer le champ non-linéaire des ondes ultrasons continue. Le modèle proposé est un outil particulièrement utile dans l'exercice des simulations numérique des faisceaux ultrasonores focalisés de haute intensité dans les tissus où les effets de la non-linéarité, de diffraction et d'atténuation sont importantes. Le modèle a été validé par des comparaisons avec d'autres établis linéaires et non-linéaires des modèles numériques ainsi que les données expérimentales publiées.

## 1. Introduction

Propagation of ultrasound is inherently a nonlinear process (Hamilton and Blackstock 1998). Nonlinear effects of ultrasound propagation such as waveform distortion and generation of harmonics can be observed in many biomedical applications of ultrasound (Carstensen and Bacon 1998). Two notable examples where the effects of nonlinear beam propagation play major roles in bioeffects of ultrasound are high intensity focused ultrasound (HIFU) and lithotripsy where intensive and focused ultrasound beams are used for various tissue treatments. Linear equations can be obtained assuming small signal approximations around equilibrium values of pressure and density. As the acoustic pressure and intensity levels are increased within the medium, more deviation from a linear model is expected

(Baker 1998). Analytical solutions to the problem of finite-amplitude propagation of acoustic beam are generally limited to simple geometries under specific simplifying conditions. Several numerical methods have been developed over the years to account for nonlinear propagation of ultrasound beams in various media (Hamilton and Blackstock 1998). These methods are typically focused on finding numerical solutions to appropriate partial differential equations (Ystad and Berntsen 1996, Khokhlova *et al.* 2001, Kamakura *et al.* 2000). One of the equations which has been widely used to describe finite-amplitude propagation of the acoustic beam is the KZK (Khokhlov, Kuznetsov, Zabolotskaya) nonlinear wave equation (Kuznetsov 1971). It accounts for combined effects of diffraction, nonlinearity and absorption and has been validated through comparison with experiments for various source geometries (Baker *et al.* 1988, Averkiou and Hamilton 1995, Baker *et al.* 1995). The KZK equation, however, is only valid in directional beams where paraxial assumption holds true. As a result it fails to be valid close to the source surface, far off the propagation axis, in highly focused sources or when the source dimensions approach one wavelength (Duck 2002). To overcome these limitations, a more general nonlinear propagation model which accounts for full diffraction was proposed (Christopher and Parker 1991, Tavakkoli *et al.* 1998). In this model the propagation of the acoustic field is carried out using a method of fractional-steps. Then, Zemp *et al.* (2003) extended the works of Christopher and Parker and Tavakkoli *et al.* to simulate nonlinear propagation of array transducers in dissipative homogeneous tissue-like media. In this work we extend the work of Zemp *et al.* to general 3D transducer geometries which are used in simulations of high intensity focused ultrasound beams.

## 2. Materials and Methods

### *Method of fractional steps*

In our model the field is calculated plane by plane in a marching scheme. Consider a partial differential equation in the form of an evolution equation as:

$$\frac{\partial f}{\partial z} = \mathrm{L}_{x,y,t}\{f\} \qquad (1)$$

where $f$ is a function of $x,y,z,t$ and $\mathrm{L}_{x,y,t}\{f\}$ is an operator which only acts on $x,y,t$ dimensions. The term $\partial f / \partial z$ on the left side of the equation enables plane by plane calculations of the function $f$ in incremental steps along the $z$ axis provided the values of $f$ is known on an initial plane (e.g. at $z = 0$). This method is commonly referred to as method of fractional steps (Ames 1992). The KZK equation can also be written in a form similar to Eq. (1) as shown below (Cobbold 2007, pp. 254):

$$\frac{\partial p}{\partial z} = \frac{c_o}{2}\int_{-\infty}^{\tau}\nabla_\perp^2 p d\tau + \frac{1}{2c_o^3\rho_o}\left[\left(\mu_B + \frac{4}{3}\mu\right)\frac{\partial^2 p}{\partial \tau^2} + \beta\frac{\partial p^2}{\partial \tau}\right] \qquad (2)$$

The first term in the right hand side of Eq. (2) represents diffraction, the second term accounts for attenuation and the third term appears because of nonlinearity. In our model, however, as will be explained in the next section, the diffraction operator is different from what is used in the KZK equation.

As it was suggested by Tavakkoli *et al.* (1998), the right hand side of Eq. (2) can be divided into three parts and rewritten in a general evolution equation form as below:

$$\frac{\partial p}{\partial z} = \mathrm{L}_D\{p\} + \mathrm{L}_A\{p\} + \mathrm{L}_N\{p\} \qquad (3)$$

where $\mathrm{L}_D\{p\} = \frac{c_0}{2}\int_{-\infty}^{\tau}\nabla_\perp^2 p\, d\tau$ is the diffraction operator, $\mathrm{L}_A\{p\} = \frac{1}{2c_0^3\rho_0}\left(\mu_B + \frac{4}{3}\mu\right)\frac{\partial^2 p}{\partial \tau^2}$ is the attenuation operator and $\mathrm{L}_N\{p\} = \frac{1}{2c_0^3\rho_0}\left(\beta\frac{\partial p^2}{\partial \tau}\right)$ represents the operator of nonlinearity. Eq. (3) demonstrates how operators of diffraction, nonlinearity and attenuation can be applied independently and then the results are added together. This is referred to as operator splitting method and has been schematically illustrated in Fig. 1(a). In our model, however, we have made use of a second-order operator-splitting method which follows a certain propagation scheme as illustrated in Fig. 1(b). Using the second-order operator splitting method would enable using larger propagation steps while maintaining the same degree of accuracy (Tavakkoli *et al.* 1998).

### *Diffraction operator*

Using the second-order operator splitting method, the first step in propagating the field from the initial plane involves a half step diffractive propagation as shown in Fig. 1(b). The main difference between this method and implementation of the KZK equation lies in the diffraction step. The diffraction term of $\frac{c_0}{2}\int_{-\infty}^{\tau}\nabla_\perp^2 p\, d\tau$ in the right hand side of the KZK Eq. (2) is only an approximation based on paraxial assumption. A more general term for diffraction should account for pressure distribution over the entire propagation plane and not only for the transversal Laplacian of pressure at each point. In this method the diffraction term in the KZK equation is replaced by a full diffraction solution. This is achieved by an angular spectrum approach which enables plane to plane diffractive propagation. If two planes are perpendicular to the $z$ axis and $\Delta z$ is the distance between them, we have (Cobbold 2007 pp.125, Zemp *et al.* 2003):

$$s(x,y,z+\Delta z) = \Im_{2D}^{-1}\left\{\Im_{2D}\{s(x,y,z)\}\times H(k_x,k_y,\Delta z)\right\} \qquad (4)$$

where the transfer function $H(k_x,k_y,\Delta z) = e^{j\Delta z\sqrt{k^2-(k_x^2+k_y^2)}}$, $k = 2\pi(nf_o)/c_o$ and $n$ is the harmonic number. The term $s(x,y,z)$ in Eq. (4) could be any field parameter such as pressure, normal particle velocity or velocity potential. In our model, we choose to propagate the normal particle velocity (i.e. $s(x,y,z) = v_z(x,y,z)$), since in our model the nonlinearity and attenuation operator acts on the normal particle velocity as discussed below.

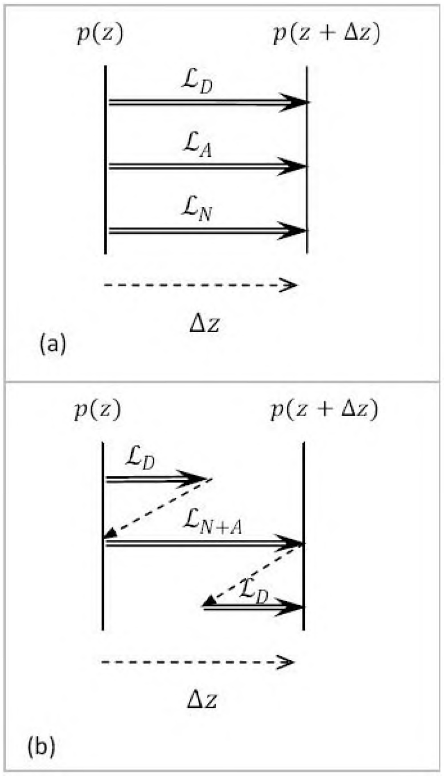


**Figure 1. Operator splitting methods. (a) First order, and (b) second order.**

***Nonlinearity and attenuation operators***

After finishing with the diffractive sub-step, the results are converted to the spatial domain and a nonlinearity and attenuation sub-step is subsequently followed as shown in Fig. 1(b). Combined effects of nonlinearity and attenuation are applied in one step using the solution obtained by Harran and Cook (Haran and Cook 1983) for nonlinear propagation of progressive plane waves in lossy media. In this method a finite number of harmonics ($N$) is captured at each plane and normal particle velocity at $z+\Delta z$ is obtained from the harmonic values of the preceding plane as below:

$$v_n(z+\Delta z)=v_n(z)+j\frac{2\pi\beta f_o}{2c_o^2}\Delta z\left[\sum_{i=1}^{n-1} i v_i v_{n-i} + \sum_{i=n+1}^{N} n v_i v_{n-i}^*\right]-\alpha_o(nf_o)^\eta v_n\Delta z \quad (5)$$

where $n$ is the harmonic number. Eq. (5) has to be repeated $N$ times to calculate all harmonics for each propagation step.

***3D source definition***

The first step in calculating the nonlinear acoustic field is to propagate the field from the surface of the transducer to a plane close-by which is called the initial plane. The reason behind this is that the method of fractional steps and the angular spectrum technique are both based on plane by plane propagation while the source geometry in general can presume any non-planar shape. The first part of the problem is to introduce a method to fully describe any source geometry and the second part is to introduce a method to capture the field of an arbitrarily shaped transducer. The first part is handled though introduction of an elements matrix and the second part is solved by using the Rayleigh diffraction integral on the surface of the source. To be able to define any source geometry and excitation, the source is broken into an array of small rectangular elements. The elements specifications (location and excitation) are then saved into a 16×N matrix which we refer to as the *Source Elements Matrix*. N is the total number of small rectangular surface elements and 16 is the number of attributes required to fully describe a surface element (Mashouf 2009).

***Full diffraction solution***

Since our method accounts for full diffraction, it is desirable that the first propagation step would also include full diffraction calculation. Furthermore it is important to have the field calculated on the initial plane as accurate as possible in order to minimize the effect of error propagation due to plane by plane propagation scheme in the method of fractional steps. In light of this, the field on the initial plane is calculated using the Rayleigh diffraction formula which is a surface integral over the entire source area as shown in Fig. 2(a). Alternatively one can use a phase shift method to estimate the field on the initial plane based on the value of the closest surface element by applying phase and amplitude correction factors as shown in Fig. 2(b). This method has been widely used for simulations of a spherically concaved transducer (Averkiou and Hamilton 1995, Christopher and Parker 1991, Filonenko and Khokhlova 2001). Although it is computationally less intensive, this method is an approximate solution and could yield in significant errors for highly focused sources (Mashouf 2009). This can be explained by noting that the field at any point on the initial plane is a sum of contributions of all surface elements and cannot be simply presented by a phase and/or amplitude correction to the corresponding value at the source surface. Once the geometry and excitation of the source are defined, the pressure is calculated at discrete points on the initial plane (e.g. point A in Fig. 2-a) by making use of the Rayleigh diffraction integral over the entire surface of the source as below (Ocheltree and Frizzell 1989):

$$P_A=\frac{j\rho_o c_o}{\lambda}\int_S V_n\frac{e^{-(\alpha+jk)r}}{r}dS \quad (6)$$

where $r$ is the distance between the field point and an infinitesimal surface element, $V_n$ is the normal velocity phasor at the element surface and $dS$ is the area of the infinitesimal surface element.

Since in our model, the source is defined by a set of small rectangular elements, Eq. (6) is realized as below:

$$P_A=j\frac{\rho_o c_o}{\lambda}\sum_{i=1}^{N}V_{ni}\frac{e^{-(\alpha+jk)r_i}}{r_i}\times w\cdot l \quad (7)$$

where $N$ is the total number of surface elements, $r_i$ is the distance between the field point and the center of the $i$th surface element, and $w$ and $l$ are the width and the length of each surface element respectively.

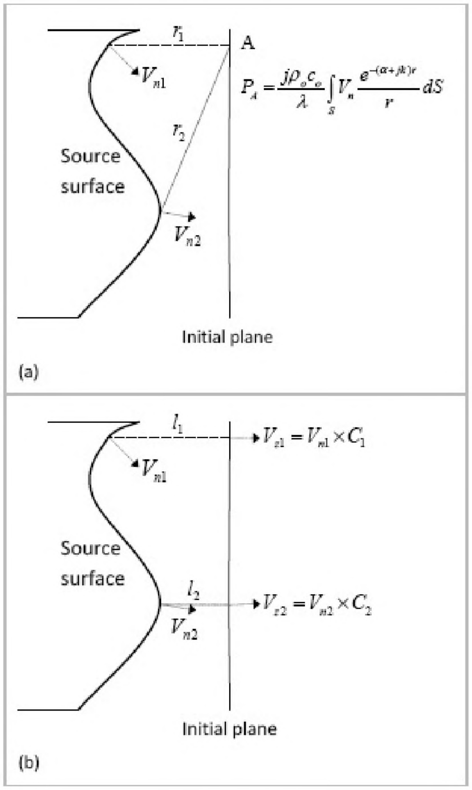


**Figure 2. Schematic demonstration of the ultrasound field calculation over an initial plane by (a) implementing the Rayleigh diffraction integral, (b) introducing phase/amplitude correction factors. In method (a) contributions of all surface elements are taken into account while in method (b) only the value of the closest horizontally located element is used to estimate the field by applying a complex correction factor ($C_1$, $C_2$).**

### *Field propagation*

Field propagation is done in incremental steps following a second-order operator splitting method as described earlier. The first step involves a half step diffractive propagation as illustrated in Fig. 1(b). Each harmonic is propagated separately by applying Eq. (4) as below:

$$\Im_{2D}\{v_z(x,y,z+(\Delta z/2))\} = \Im_{2D}\{v_z(x,y,z)\}\times H(k_x,k_y,(\Delta z/2)) \quad (8)$$

where the transfer function $H(k_x,k_y,\Delta z/2) = e^{j(\Delta z/2)\sqrt{k^2-(k_x^2+k_y^2)}}$ and $\Delta z$ is the size of each propagation step. The 2D Fourier transform of normal particle velocity on the initial plane is can be obtained as (Mashouf 2009):

$$\Im_{2D}(v_z(x,y,z_0)) = w^2\mathrm{sinc}(w\frac{k_x}{2\pi}, w\frac{k_y}{2\pi})\times \sum_{i=1}^{N} v_i e^{-j(k_x x_{ci}+k_y y_{ci})} \quad (9)$$

where $N$ is the total number of the array elements.
Accordingly the right hand side of Eq. (8) can be obtained by multiplying Eq. (9) to the transfer function $H$.
After finishing the diffraction substep**,** the result is converted back to spatial domain using inverse 2D Fourier transform and a nonlinear substep is subsequently followed as shown in Fig. 1(a). The process is then repeated to propagate the field along the $z$ direction.

### *Spatial sampling*

Since performing the 2D inverse Fourier transform of Eq. (8) is analytically not possible, the right hand side of this equation is discretized along $k_x$ and $k_y$ dimensions and an inverse discrete Fourier transform is used instead. The sampling of $k_x$ and $k_y$ dimensions should be performed to capture the field variations adequately. If $\Delta x$ is the desired sampling interval on a propagation plane over the $x$ dimension, the maximum spatial frequency component of the 2D discrete Fourier transform of the field over the $k_x$ dimension is given by:

$$k_{x-\max} = \frac{\pi}{\Delta x} \quad (10)$$

As mentioned before, the first propagation step involves a diffractive sub-step which is calculated as below (see Eqs. (8) and (9)):

$$v_z(x,y,z_0+(\Delta z/2)) =$$
$$\Im_{2D}^{-1}\left\{w^2\mathrm{sinc}(w\frac{k_x}{2\pi}, w\frac{k_y}{2\pi})\times \sum_{i=1}^{N} v_i e^{-j(k_x x_{ci}+k_y y_{ci})}\times H(k_x,k_y,(\Delta z/2))\right\} \quad (11)$$

Studying a $\mathrm{sinc}(x)$ function shows that at around $x=5$, its amplitude has already reduced to about 5% of the maximum. Hence, the values of $w\frac{k_x}{2\pi}$ in Eq. (11) should extend beyond 5 in order for variations to be adequately captured. In other words:

$$w\frac{k_{x-\max}}{2\pi} \geq 5 \quad (12)$$

Substituting $k_{x-\max}$ form Eq. (10) into Eq. (12), the following criteria for the sampling interval is obtained:

$$\Delta x \leq w/10 \quad (13)$$

Similar criterion applies for sampling interval along $y$ direction. In other words the spatial sampling on the propagation plane should be at least ten times finer than that of the initial plane.

### *Enhanced pressure formulation*

In the methodology described above, the values of normal particle velocity ($\boldsymbol{v}_z$) are calculated on each propagation plane. Other acoustic parameters such as pressure should be derived from the calculated values of normal particle velocity. A simple method to convert normal particle velocity to pressure, is through the linear impedance relation as below:

$$P(x,y) = \rho_o c_o \cdot V_z(x,y) \quad (14)$$

This formula, however, is only accurate for a plane wave travelling along the $z$ axis in an inviscid medium. As we will see later, Eq. (14) can be significantly in error in nonplanar fields. A more general formula which is valid in any field configuration (such as spherical, cylindrical or focused beams) is expressed as below (Liu and Waag 1997):

$$P(x,y)=\Im_{2D}^{-1}\left\{\Im_{2D}\{V_z(x,y)\}\frac{\rho_o c_o k}{\sqrt{k^2-(k_x^2+k_y^2)}}\right\} \quad (15)$$

Eq. (15), however, includes a singularity in spatial frequency at a circle with radius of $k$ which is centered at origin and known as radiation circle. As a result, numerical methods to calculate the inverse Fourier transform of Eq. (15) may either fail or generate considerable amount of computational noise in the output. Eq. (15) assumes propagation in a lossless medium. In the presence of viscous loss, Eq. (15) takes the following form (see Mashouf (2009) for the full derivation):

$$P(x,y)=\Im_{2D}^{-1}\left\{\Im_{2D}\{V_z(x,y)\}\frac{\rho_o c_o \underline{k}^2}{k\sqrt{\underline{k}^2-(k_x^2+k_y^2)}}\right\} \quad (16)$$

where $\underline{k}^2=\dfrac{k^2}{1-j(2\alpha/k)}$.

In a lossless medium, $\underline{k}^2=k^2$ and Eq. (16) reduces to Eq. (15) as expected. It is interesting to note that in the presence of viscous loss, the transfer function of Eq. (16) will no longer contain a singularity. Since in a physical medium there's always some loss, the problem of singularity can therefore be avoided by using Eq. (16).

It can be also shown that in case of a plane wave propagating in an inviscid medium Eq. (16) reduces to the impedance relation of Eq. (14) as expected. In a plane wave propagating along the z direction, normal particle velocity phasor is a constant anywhere on a plane perpendicular to the z-axis. In other words $V_z(x,y)=V_o$, where $V_o$ is a constant. As a result 2D Fourier transform of $V_z(x,y)$ is a Dirac impulse function as below:

$$\Im_{2D}\{V_z(x,y)\}=V_o\times\delta(f_x,f_y)=V_o\times\delta\left(\frac{k_x}{2\pi},\frac{k_y}{2\pi}\right)=V_o\times 4\pi^2\delta(k_x,k_y) \quad (17)$$

Substituting Eq. (17) into Eq. (16) and noting that the $\delta(k_x,k_y)$ is zero everywhere except at $k_x=k_y=0$, results in:

$$P(x,y)=\Im_{2D}^{-1}\left\{V_o\times 4\pi^2\delta(k_x,k_y)\times\frac{\rho_o c_o \underline{k}^2}{k\sqrt{\underline{k}^2-(0+0)}}\right\} \quad (18)$$

or

$$P(x,y)=\Im_{2D}^{-1}\left\{V_o\times 4\pi^2\delta(k_x,k_y)\times\frac{\rho_o c_o \underline{k}}{k}\right\} \quad (19)$$

Since in an inviscid medium $\underline{k}=k$, Eq. (19) can be simplified further as below:

$$P(x,y)=\rho_o c_o\Im_{2D}^{-1}\{V_o\times 4\pi^2\delta(k_x,k_y)\} \quad (20)$$

Conversely, the inverse 2D Fourier transform of a delta function is a constant in space. In other words:

$$P(x,y)=\Im_{2D}^{-1}\{V_o\times\delta(f_x,f_y)\}=\rho_o c_o\times V_o \quad (21)$$

which is the well-known impedance relation.

Eq. (16) enables conversion of particle velocity normal to a plane to the values for pressure on the same plane. Since in our method the values of normal particle velocity are only known over the extent of propagation planes, Eq. (16) serves as an ideal tool to accomplish conversion to the values of pressure.

We refer to pressure obtained using Eq. (16) as "enhanced pressure" formulation to make distinction from the impedance pressure formulation expressed by Eq. (14). In what follows we demonstrate how impedance pressure of Eq. (14) can be significantly in error in non-planar fields.

***Field of a concave spherical source***

Another example of a non-planar acoustic field is the field of a concave spherical source. It is important to investigate the degree of error in the plane wave approximation used in this geometry that is frequently used in many biomedical applications including HIFU. We study three transducers with different $F$ numbers to demonstrate how the source curvature affects the results. Focal distance of all transducers are equal (20mm) but they have different diameter of apertures as shown in Figs. 3(a). As a result, the associated $F$ numbers of the transducers will be 2 and 1. Figs. 3(b) and (c) display the lateral pressure profiles on the focal plane of each transducer. Each graph shows two pressure profiles which have been obtained using different methods namely the Rayleigh integral and the impedance formula. The Rayleigh integral was calculated using Eq. (7), and the linear impedance formula makes use of the plane wave approximation given by Eq. (14) as described before.

As it can be seen in Fig. 3, the difference between the actual pressure and the plane wave approximation rises as the source curvature increases (or $F$ number decreases). This is expected as deviation from a plane wave is more pronounced in the case of a highly focused source versus a slightly focused source. The second point to note about pressure profiles presented in Fig. 3, is that the actual pressure is almost always higher than what is predicted by an impedance approximation. This can be explained by the fact that in the linear impedance formula, only the normal component of particle velocity ($\boldsymbol{v}_z$) is used to estimate the pressure, but in general non-planar fields, lateral components of particle velocity (i.e. $\boldsymbol{v}_x$, $\boldsymbol{v}_y$) are also present and could have substantial amplitudes. Lateral components of the particle velocity would also contribute to creating a pressure build up.

## 3. Results

The KZK equation has been widely accepted as a gold-standard model to simulate nonlinear ultrasound propagation. In order to validate our methodology and test the performance of our model in nonlinear mode, we compared the results obtained using our model with published KZK simulations and experimental results. In their 1995 paper, Averkiou and Hamilton (Averkiou and Hamilton 1995) presented results of the KZK simulations for a concaved spherical source in water and compared them with experimental data. In order to do a comparative study, we implemented identical source and medium parameters (as used by Averkiou and Hamilton) in our model. The parameters used in this simulation include: Radius of

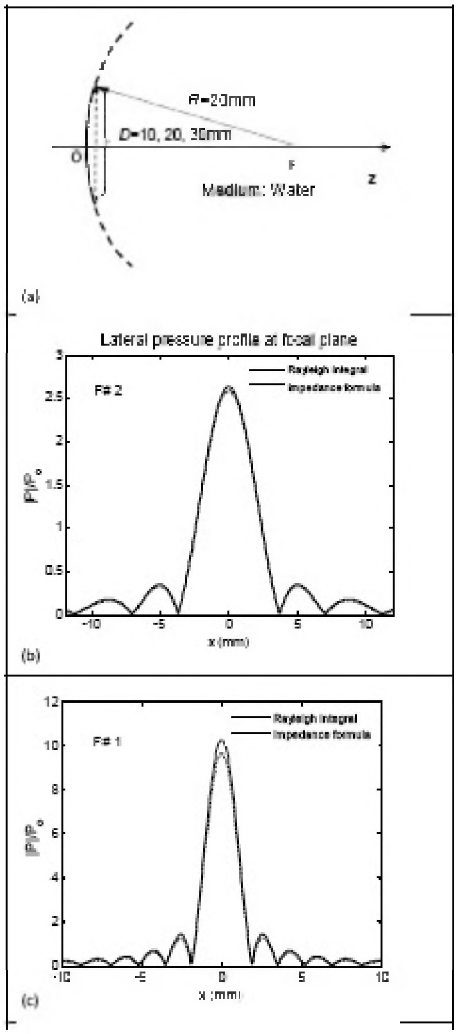


**Figure 3. (a) Concentric concaved spherical sources with different diameters of aperture (*D*) to study the effect of curvature in calculation of pressure. Higher values of *D*, corresponds to higher degrees of focusing. Comparison of impedance pressure versus actual pressure at $f_0$ = 1 MHz on the focal plane of a (b) moderately focused and (c) a highly focused source.**

curvature ($R$) = 160 mm, aperture diameter ($D$) = 37.6 mm, source pressure ($P_o$) = 92.5 kPa, source frequency ($f_o$) = 2.25 MHz, attenuation coefficient at 2.25MHz($\alpha$)= 0.1645 Np/m, and coefficient of nonlinearity ($\beta$)= 3.5.

Fig. 4 below shows the lateral pressure profiles for fundamental and three harmonics at pre-focal ($z$ = 100 mm), focal ($z$ = 160 mm), and post-focal ($z$ = 250 mm) planes. The results of Averkiou and Hamilton include both experiment (solid line) and theoretical (dotted line) results. As it can be seen in Fig. 4, very good agreement exists between our results and those obtained from the KZK nonlinear model.

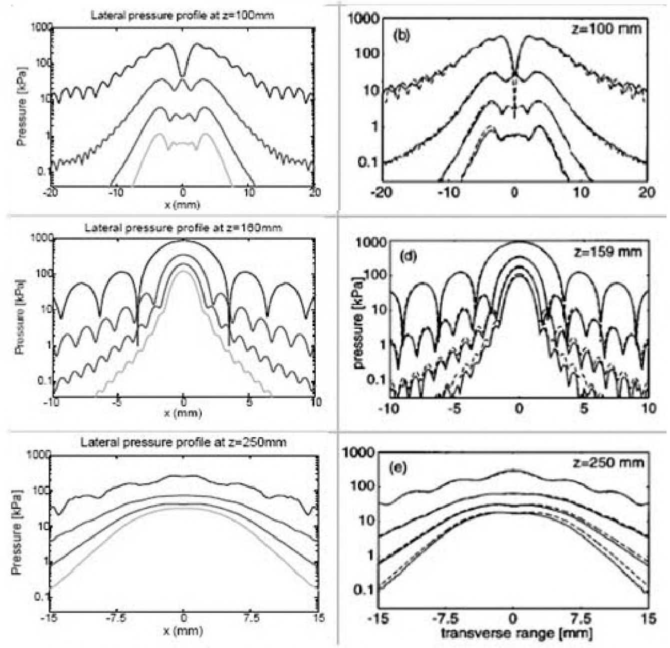


**Figure 4. Lateral pressure profiles at various axial locations (top panel: pre-focal, middle panel: focal plane, bottom panel: post-focal). Left column: Our model, Right column: Experiment (solid line) and KZK results (dotted line) by Averkiou and Hamilton, 1995.**

## 4. Discussions and Conclusions

In this work a continuous wave nonlinear propagation model based on a second-order operator splitting method was presented. The model was made more versatile by introducing a 3D arbitrary source definition capability and by converting the values of normal particle velocity to pressure across the propagation plane using an enhanced formula in dissipative media. Using our numerical model, one can define any 3D source geometry. The amplitude and phase of the normal particle velocity can also be arbitrarily defined and varied across the source surface as appropriate. This would enable simulations of transducers of arbitrary geometries and excitations. The full diffraction and enhanced pressure formula enable calculation of the acoustic pressure in a given plane in terms of the normal particle velocity in the same plane (see Eq. (16)). We demonstrated that for a concave spherical source with dimensions and excitation frequencies around those of interest in biomedical ultrasound, the impedance relation based on the plane wave approximation yields substantially lower pressure values. A particular area of interest is the focal region of focused sources where a significant difference between the two methods is observed. The difference in predicted pressure leads to even more disparity in intensity values as the intensity is related to pressure by the power of two in nonlinear regime according to the approximate formula $I_{total} \approx \sum_{n=1}^{N} I_n = \sum_{n=1}^{N} \frac{|P_n|^2}{2\rho_0 c_0}$ which simply states that the total intensity in a nonlinear field is equal to the sum of intensities of each harmonic (Bailey *et al.* 2003). Moreover, since the intensity values are directly proportional to heat generation rate, according to the approximate formula $Q_{total} \approx \sum_{n=1}^{N} 2\alpha_n I_n$ (Bailey *et al.* 2003), this will in turn affects temperature predictions as well. Accurate temperature calculations are highly demanded in areas such as ultrasound hyperthermia and/or high intensity focused ultrasound (HIFU) where focused nonlinear ultrasound beams are used to induce controlled tissue temperature elevation. Through implementation of the enhanced pressure formula we managed to resolve the singularity issue in the transfer function of normal particle velocity to pressure by making use of $\underline{k}$ or a complex wave number. By using a complex wave number, the singularity in Eq. (15) is eliminated and calculating the inverse 2D Fourier transform becomes a well-posed problem. Alternatively this singularity can be avoided by implementing a narrow band-stop filter around the singularity. However the complex wave number method offers benefits in terms of calculation accuracy and efficiency over the filtering method (Mashouf 2009).

We verified our results by comparison to simulation and experimental data available in the literature. A great agreement observed both in linear and nonlinear regimes. The next steps in this work include expansion of the current model to include temperature rise predictions, multilayer media and pulse mode propagation. The temperature simulations are carried out by calculating the heat deposition rate within the medium and coupling with an enhanced bio-heat transfer equation. Multilayer medium can be introduced into the model by changing the medium properties in each propagation step accordingly.

## ACKNOWLEDGMENTS

This work was partially supported by the Ryerson Start-up Research Fund and the Natural Sciences and Engineering Research Council (NSERC) of Canada Discovery Grant that were awarded to J. Tavakkoli.

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# EXPERIMENTAL EVALUATION OF VEHICLE CABIN NOISE USING SUBJECTIVE AND OBJECTIVE PSYCHOACOUSTIC ANALYSIS TECHNIQUES

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## ABSTRACT

Given the automotive industry's awareness of the importance of the perception of noise, vibration and harshness (NVH) emissions, there is an increased focus on the sound quality of automotive vehicle cabin noise. Psychoacoustic analysis using acoustic pressure measurements taken inside the vehicle cabin was performed. Suspension vibration measurements from several structural positions were also taken to evaluate vibration excitations. The goal was to be able to predict the psychoacoustic impact at the driver's ear position using the suspension vibration data measured outside the vehicle. Using the vibration data, it was possible to evaluate the transfer path of the excitation energy into the vehicle cabin. Using this, a correlation between the predicted in-cabin psychoacoustic results using the outside vibration measurement data and the direct psychoacoustic calculations from the in-cabin noise measurements was proven possible with some inherent limitations.

## SOMMAIRE

Compte tenu de la reconnaissance par l'industrie d'automobile de l'importance de la perception des émissions de NVH, il y a maintenant plus de concentration sur la qualité sonore du bruit à l'intérieur des automobiles. L'analyse psycho-acoustique a été effectue avec l'aide des mesures des pressions acoustiques à l'intérieur du véhicule. Les mesures des vibrations de la suspension de l'automobile ont été prises à plusieurs positions structurelles pour évaluer les excitations de vibration. En utilisant les données de bruit et de vibrations, il a été possible d'évaluer le moyen de transfert de l'énergie d'excitation de la suspension à l'intérieur du véhicule. Une tentative d'établir une corrélation entre les mesures de bruit et de vibrations et les observations psycho-acoustiques a été possible avec certaines limites.

## INTRODUCTION

In terms of noise generation, the automobile is simply a set of different systems that when excited at specific frequencies will eventually lead to the creation of noise. This statement was of course also true in the early days of automobiles, however, it was always taken to be a secondary issue that was simply accepted since more important factors had to be addressed. Both technology improvements and legislative advancements have since led to the evolution of the modern automobiles and the development of new performance targets, some of which target noise.

Today, automakers invest significant time and money in research and development associated with the reduction of vehicle noise. Since automakers are also more aware of the importance of the perception of noise, vibration and harshness (NVH) emissions, there is also an increased focus on the sound quality of vehicle cabin noise. Consumers also demand safer and more comfortable vehicles, especially given the significant increased use of cellular phones, entertainment and interactive voice controls in vehicles. As part of this, the evaluation of vehicle cabin acoustics using psychoacoustic metrics has become an essential tool for the improvement of today's vehicles. It would be very useful if these psychoacoustic impacts at the driver's ear position could be determined indirectly by using noise or vibration measurement data taken at the source location, usually outside of the vehicle or under the hood. This would result in saving of time and money by being able to use existing measurement data, often supplied by tier one and two suppliers, without the need to collect additional binaural noise data using a vehicle chassis dynamometer for specific psychoacoustic post processing.

A significant source of unwanted cabin noise is the result of external sources such as engine components, drivetrain and road-induced excitation of the vehicle suspension all of which propagate into the vehicle cabin. [1] [2]. The purpose of this study is to investigate whether vehicle suspension noise and vibration data could be used to predict the sound quality metrics of loudness, fluctuation strength and roughness as well as sound pressure level at the driver's ear position. Specifically, an evaluation of the transmission paths of the excitation energy into the vehicle cabin from road induced noise and vibration using frequency response functions is performed. As part of this, binaural noise data was also taken in the vehicle and post processed to calculate the same sound quality metrics. The objective is to establish a correlation between the suspension measurements taken outside of the vehicle to the psychoacoustic calculation results based on measured noise data taken inside the vehicle at the driver's ear position.

## THEORY OF PSYCHOACOUSTIC METRICS

The study of psychoacoustics involves the quantification of the human perception of sound [3]. In other words, it aims to correlate physical acoustic parameters to actual sound perception. There are many different psychoacoustic metrics that are used today. The ones considered in this study include Zwicker Loudness, Roughness and Fluctuation Strength. A description of each follows.

Zwicker Loudness - To understand the metric of Zwicker loudness, an understanding of frequency sensitivity and masking is also necessary. For this, the following parameters need also to be considered:

- Frequency and sound pressure level (SPL) level influence
- Critical Bands and
- Frequency Masking

Sound is not perceived equally across the entire frequency range. The human ear is most sensitive at frequency within the approximate range of 2.5 kHz to 5 kHz. Further from 4 kHz in either direction, sensitivity of human hearing decreases. In order to characterize these differences, equal loudness curves (Figure 1) have been developed and evolved over the years. The latest version of these curves have been standardized by ISO 226:2003 [4] and illustrate the human sensitivity of sounds at different sound pressure levels as a function of frequency. Loudness unity is taken to be at a 1 kHz pure tone having an SPL of 40 dB and is given as 1 sone. This reference value is also often expressed as a loudness level having a value of 40 phons. However, the expression of this metric using the units of sones has the advantage that the loudness can be expressed in a linear manner. In other words for a given a noise source which is increased to be twice as loud, the perceived loudness value is also doubled.

It is common practice that the frequency content of a signal be given in terms of full or fractional octave bands. The human hearing system instead filters sound with respect to frequency using bandwidths referred to as "Critical Bands" for which there are 24 bands in total [5][6].

It has also been shown that masking of a sound can occur for sounds which are present within adjacent bands. This phenomenon of frequency masking, which is accounted for in the calculation of Zwicker loudness, can occur when two nearby coexist as illustrated in Figure 2. Here, the dashed curve represents the masking pattern of the masker tone. The term "frequency masking" comes from the fact that if two signals are present in the same or nearby frequency band, the stronger signal will overshadow the weaker signal. Heard separately, one is able to clearly distinguish between them, however, once they occur simultaneously, the sound with the lower SPL level will be less audible or in the case where the masked tone is below the masking pattern, it will not heard at all. It should also be noted that as a masker tone becomes louder, the right side of the masking pattern slope becomes flatter and results in a greater ability to mask sounds having frequencies further away from the frequency of the masker tone. This effect is called the "non-linear upward spread of masking". [7]

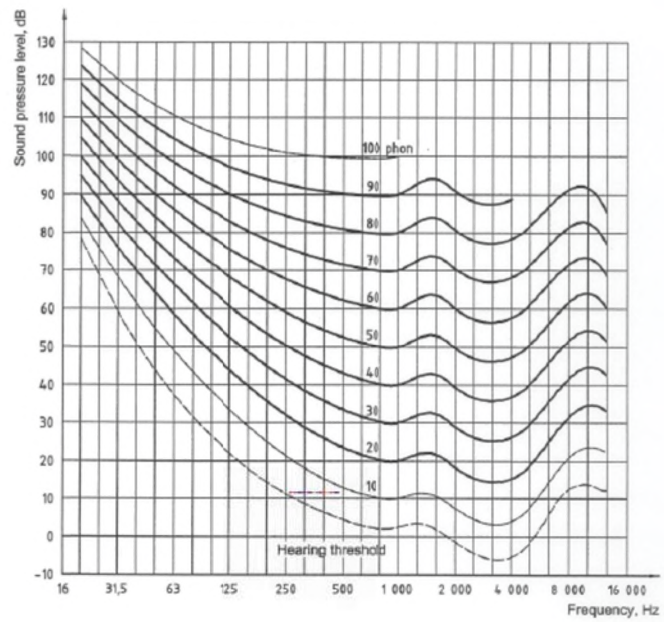


**Figure 1**: *Equal Loudness Curves* [4]

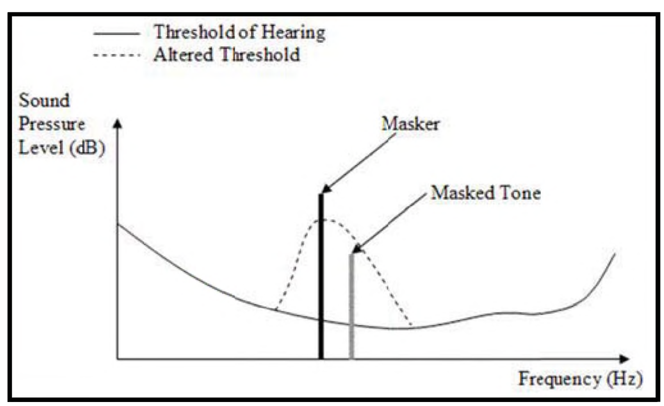


**Figure 2:** *Frequency Masking* [8]

Examination of the necessary derivations given by Fastl and Zwicker [9] including "specific loudness" ( $N'$ ) begins with the assumption that a relative change in intensity or excitation level ( $E$ ) is proportional to a relative change in perceived loudness. We have:

$$\frac{\Delta N'}{N'} = k\frac{\Delta E}{E} \quad (1)$$

where: $k$ represents the proportionality constant

Zwicker and Fastl gave an approximation for the specific loudness for each critical band as:

$$N' = 0.08\left(\frac{E_{TQ}}{E_O}\right)^{0.23}\left(\left(0.5+\frac{E}{2E_{TQ}}\right)^{0.23}-1\right)\frac{sone}{Bark} \quad (2)$$

where: $E_{TQ}$ represents the excitation level at threshold of quiet and $E_{TQ}$ is the excitation level at reference intensity of $10^{12}\left(W/m^2\right)$ and each having units of decibel.

The total loudness ($N$) can be found as the sum of specific loudness $N'$ across all of the critical bands with critical band width ($dz$).

$$N = \int_0^{24Bark} N'dz \quad (3)$$

Modulating Metrics - Modulating sounds within a specific frequency range can produce two different hearing sensations. In the case of low frequency modulation (below 20 Hz) fluctuation strength is the relevant metric. For the frequency range between 20-300 Hz, the modulation may be described using Roughness. Both of these metrics are modeled in a similar manner (Figure 3) and show proportionality with respect to both modulation frequency ($f_{\mathrm{mod}}$) and temporal masking depth (ΔL) [10].

$$F.S. \sim \frac{\Delta L}{\frac{f_{\mathrm{mod}}}{4Hz}+\frac{4Hz}{f_{\mathrm{mod}}}} \quad (4)$$

and

$$R \sim \Delta L * f_{\mathrm{mod}} \quad (5)$$

Modulated sounds for modulation frequencies below 20 Hz are characterized using Fluctuation Strength which is strongly dependent on the modulation frequency ($f_{\mathrm{mod}}$) and temporal masking depth ($\Delta L$). A modulation frequency of 4 Hz is found to be perceived as most annoying. [11] The temporal masking depth ($\Delta L$) according to Zwicker and Fastl model can be approximated using both maximum ($N'_{\max}$) and minimum ($N'_{\min}$) values of specific loudness for each critical band. The term dB/Bark is simply a unit conversion.

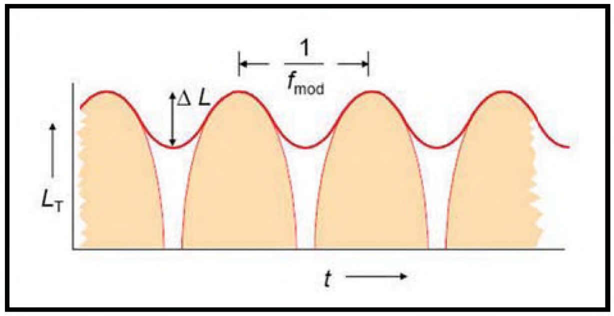


**Figure 3**: *Model for "fluctuation strength" & "roughness"* [10]

$$\Delta L \approx 4\log\left(\frac{N'_{\max}}{N'_{\min}}\right) \quad (6)$$

Substituting Eq. 3.7 into Eq. 3.5 fluctuation strength can be found to be:

$$F.S. = \frac{0.008 * \int_0^{24Bark} \frac{4\log\left(\frac{N'_{\max}}{N'_{\min}}\right)dB}{dB/Bark}dz}{\frac{f_{\mathrm{mod}}}{4Hz}+\frac{4Hz}{f_{\mathrm{mod}}}} \quad (7)$$

Even though the model shown in Figure 3 illustrates both fluctuation strength and roughness, the sensation of roughness when compared to fluctuation strength is actually quite different. The main difference with Roughness from a subjective perspective is the rapid amplitude modulation in the frequency range between 20 and 300 Hz. Temporal masking depth ($\Delta L$) depends on the critical band rate, so continuing from Equation 5, a more accurate proportionality is:

$$R \sim f_{\mathrm{mod}} \int_0^{24Bark} \Delta L(z)dz \quad (8)$$

Finally, according to Zwicker and Fastl Roughness is calculated as:

$$R \sim 0.3\frac{f_{\mathrm{mod}}}{1kHz}\int_0^{24Bark}\frac{20\log\left(\frac{N'_{\max}}{N'_{\min}}\right)dB}{dB/Bark}dz \quad (9)$$

Frequency Response Functions & Coherence - When considering dual signal analysis, the frequency response function (FRF) is a particularly valuable tool. It is used to represent the relationship between the input and the output signal of the system upon the transformation of data from the time to frequency domain. Figure 4 illustrates an overview of the required steps for the estimation of FRFs. There are four main stages: recording, analysis, averaging, and post-processing.

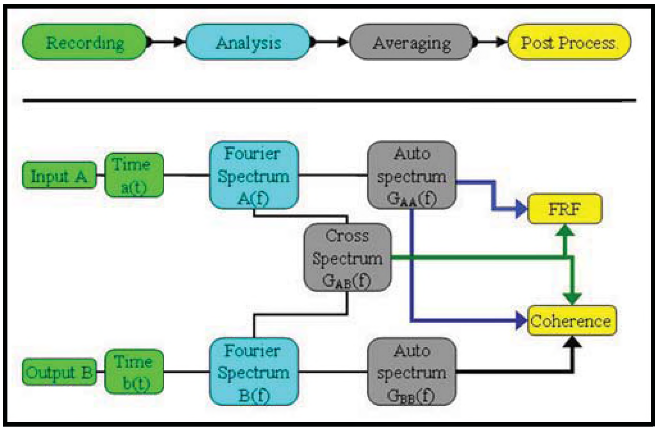


**Figure 4**: *Schematic representation of dual signal analysis*

The recorded time signal is transformed to the frequency domain via the FFT process. Auto-spectrums of both input and output signal individually as well as the cross-spectrum between them are obtained through the process of averaging. This finally leads to the derivation of the frequency response function and coherence.

The Fourier spectrum of the signal a(t) and b(t) is given as A(f) and B(f) respectively and can be found as:

$$A(f) = \int_{-\infty}^{\infty} a(t) e^{-j2\pi ft} dt \qquad (10)$$

This quantity is complex containing both modulus and phase. In order to find the auto-spectrum, $G_{AA}$ (i.e. $G_{BB}$), Fourier spectrum $A(f)$ (i.e. $B(f)$), is multiplied by its complex conjugate and averaged. This will produce a real and positive number because of the complex squaring.

$$G_{AA} = \overline{A^*(f) * A(f)} \qquad (11)$$

Similarly, the cross-spectrum $G_{AB}$ is defined as:

$$G_{AB} = \overline{A^*(f) * B(f)} \qquad (12)$$

Because of the fact that this term is complex, it contains the phase between the output and the input of the system.

Once we have all three fundamental spectra ($G_{AA}$, $G_{BB}$ and $G_{AB}$), the frequency response function can be found as:

$$H_1(f) = \frac{G_{AB}}{G_{AA}} \qquad (13)$$

Finally, to show the degree of linearity between the two signals in the frequency domain, and to validate frequency response function, the Coherence function is used. It can be calculated in the following way:

$$\gamma^2(f) = \frac{|G_{AB}|^2}{G_{AA} * G_{BB}} \qquad (14)$$

where: $0 \le \gamma^2(f) \le 1$

Coherence can range from zero to one such that if equal to one at given frequency, the system has perfect causality at that specific frequency and that the output is simply caused entirely by the input. On the other hand, if the coherence is equal to zero, the output is caused entirely by another uncorrelated source. For the case of low levels of coherence, this may be caused by some extraneous noise at either the input or the output of the system or that the some other non-correlated input may be passing through the system [12]. Coherence is often used along with the frequency response function for validation and in to show the degree of linearity between an input and output signal in the frequency domain.

## EXPERIMENTAL DETAILS

For this investigation, acoustic pressure measurements were taken inside the vehicle cabin at the driver's left ear location using conventional microphones as well as at the passenger's ears position with a binaural head for the evaluation of the resulting sound quality. The acquisition recording time was 15 seconds per run performed in a hemi-anechoic chamber with the vehicle driven and motored on a 4-wheel-drive dynamometer.

The vehicle used for the experiments was a 2004 Chevrolet Epica Notchback LS. The Epica is a front wheel drive vehicle powered by an inline six-cylinder engine mounted transversely. The overall body dimensions are given in Figure 5.

To prevent acoustic rattling, loose and body parts were removed and secured as shown in Figure 6. The vehicle's airbags were also removed during the tests for safety reasons and is illustrated in Figure 7.

In order to mount and secure the accelerometers on the suspension points, brackets were made and installed at the measurement positions. Aluminum brackets were machined and bolted on the top of the McPherson strut and next to the wheel hub both on the driver's side of the vehicle as shown in the Figure 8 below.

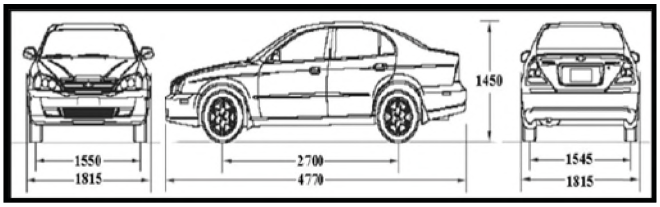


**Figure 5:** *Epica LS Dimensions in mm* [13]

**Figure 6:** *(Left) original rear end; (Right) modified rear end*

**Figure 7:** *(Left) original Epica's interior; (Right) modified interior-airbag removed*

**Figure 8:** *(Left) top of the McPherson strut; (Center) bracket next to wheel hub; (Right) lower A- arm*

An accelerometer was also attached to the suspension link on a flat portion on the bottom of the lower arm. All of the brackets were installed with the vehicle maintained at the normal riding height. They were also specifically oriented such that the accelerometer's positive x-direction was facing front of the car, the positive z-direction was facing the top of the car and the positive y-direction was oriented toward the left side of the vehicle. Microphones were located inside the vehicle cabin as well as outside of the car near the front driver side wheel. There were a total of four microphones used in the experiment. One microphone was mounted at the left side of driver's headrest (Figure 9 - *middle*) while the second was installed on the outside of the cabin next to front wheel on the driver's side (Figure 9 - *right*). For this case, a microphone windscreen was used to protect the diaphragm and reduce any wind noise effects. The other two microphones were located inside the binaural head which was installed at the passenger's seat position (Figure 9 - *left*). The head assembly was placed on a stand so as to resemble the ride height of a typical person positioned in the seat.

**Figure 9:** *(Left) passenger's seat with binaural head; (Middle) driver's seat with conventional microphone; (Right) microphone next to the front wheel*

The testing was done at the Brüel & Kjær Application Research Center (ARC) in Canton, Michigan, USA within a semi-anechoic room equipped with a 4WD dynamometer as illustrated in Figure 10.

**Figure 10:** *4WD dynamometer ARC anechoic chamber*

The function of the chassis dynamometer was to replicate the rolling resistance that the vehicle would experience while driven on the road. In order to ensure accurate sound measurement with minimal background noise, testing was done in a hemi-anechoic room where only the floor was reflective. The walls were treated with sound absorbing wedges thus minimizing both ambient noise and reflections and providing a room cut-off frequency of approximately 90 Hz. The dynamometer rollers had a road surface imprint adhered to them to better replicate a real driving surface taken from a local proving ground test track. For cases of self-driven and motored vehicle, the testing speed, engine load, air circulation and exhausts emissions were controlled remotely from the controlling room located next to the test cell. Data acquisition was performed during motored and driven conditions. For both cases, the following operation conditions were considered:

- Idling/Ambient
- Steady speeds (20, 40, 50, 60 & 80 km/hr)

- Acceleration run-up from 0 to 80 km/hr

For the vibration acquisition, the accelerometer positioned on the wheel hub and was stationary for the entire experiment. The second accelerometer was moved between tests, initially located on the lower A-arm it was later moved to the top of the McPherson strut. Because of the effect of heat generation by the brake calliper, a piezoelectric accelerometer was to used due to its heat resistant qualities. Six Brüel & Kjær Type 2635 and Type 2626 amplifiers were used to condition the two 3-axis accelerometers. For each steady speed run, 15 second data was collected, whereas for the acceleration tests, approximately 30 seconds of acquisition was required due to the maximum possible acceleration rate of the dynamometer.

## DATA ANALYSIS

Two commercial software packages were used for the purpose of calculation of psychoacoustic metrics. The pure aqcuired time signals were used for the determination of the frequency response functions (FRF) and coherence between the pressure and acceleration excitations from outside of the vehicle and the sound pressure obtained inside the cabin,. Separate Matlab codes were also made to estimate pressure levels using these FRFs.

The psychoacoustic metrics of Loudness, Roughness and Fluctuation Strength as well as the A-weighted SPL at steady driving speeds were processed. For this purpose, a software program called dBSonic was used. Selected signals from all three microphones located in the vehicle cabin were considered at all steady speeds in both cases of self-driven and motored vehicle. This particular software allowed for the selection of the desired sound files and by specifying specific parameters, for example, frequency weighting for SPL, window type or window overlap for FFT spectrograms or type of sound field and interval between points for psychoacoustic metrics, the desired results can be obtained. Figure 11 shows a schematic representation of an analysis performed using dBSonic.

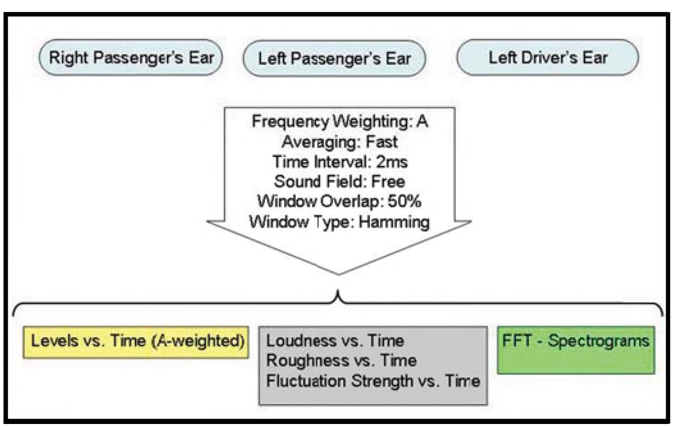


**Figure 11:** *Schematic representation of analysis performed using dBSonic.*

Estimation of the relationship between the input and the output of the system was performed using the two different software programs dBFA and Matlab. For this process, each of the ten input signals needed to be correlated to each of the three output signals. Two different trials were also considered at six different steady speeds. Additionally, two different driving conditions were considered which gave frequency response functions and coherence functions for correlation between the sound pressure from outside and sound pressure inside the vehicle cabin.

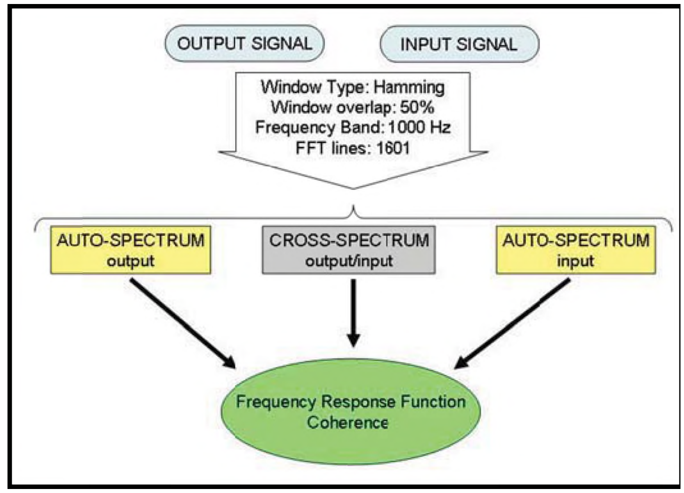


**Figure 12:** *Schematic representation of analysis performed using dBFA.*

For the first case, the raw signal was loaded into dBFA for post-processing. In order to generate the frequency response and coherence functions between any input and output signal a few steps must first be completed as illustrated in Figure 12. First, the two signals of interest are selected. And the auto-spectrum and cross-spectrum of each of them are found using narrow band spectrum analysis. The FFT window type was then selected as well as the window overlap and the number of FFT lines. To reduce computational time, the frequency band was specified in this case to be limited to 1000 Hz. The cross-spectrums were calculated in the same manner making sure that all of the selected parameters match the ones used for auto-spectrum calculations to be able to compute the Transfer Functions, FRFs and Coherence values.

From the Auto-spectrums $G_{AA}$ (input) and $G_{BB}$ (output) as well as the cross spectrum $G_{AB}$ between the input and the output, analysis produces the transfer function:

$$H_1(f) = \frac{G_{AB}}{G_{AA}}$$

and Coherence:

$$\gamma^2(f) = \frac{|G_{AB}|^2}{G_{AA} * G_{BB}}.$$

Given that the acquisition software does not allow for the calculation of frequency response functions between pressure and/or acceleration or any of the psychoacoustic metrics, Matlab codes were developed using the basic built-in functions within Matlab for the calculation of the auto-spectrums and the cross-spectrums separately. These were then combined to calculate the FRFs and coherence using built-in functions for direct estimation of both FRFs and coherence.

The Matlab function was used to estimated the transfer function of the system with input A and output B using Welch's averaged periodogram method. Coherence is also estimated in the similar matter. They are both given as:

[Txy, F] = tfestimate (A, B, WINDOW, NOVERLAP, NFFT, Fs, 'whole')

[Cxy, F] = mscohere (A, B, WINDOW, NOVERLAP, NFFT, Fs, 'whole')

Where:

| | |
|---|---|
| A | Input Signal (Time Domain) |
| B | Output Signal (Time Domain) |
| WINDOW | Specific Window function |
| NOVERLAP | Percentage of overlap between segments |
| NFFT | Number of FFT points |
| Fs | Sampling frequency |
| 'whole' / 'half' | Whole or half of the Nyquist interval |

Consider for example the case where the vehicle was self driven at the steady speed of 40 km/hr. Given that there were two trials per speed, trial #1 was used to find frequency response functions between input and output signal. The calculated FRF would be then used to estimate the output signal from the second trial. The relationship between the input and the output of the system can be represented as:

$A(f) * H_1(f) = B(f)$ where H1 is the FRF of the system.

This expression is valid in the frequency domain so once the output has been estimated, it would be given in the frequency domain. As such, the inverse of the FFT of the signal was required to obtain the signal in the time domain.

At this point, a comparison was possible between the original and predicted levels to see if the FRFs are valid as well as the resulting confidence levels (Figure 14). Also obtained were the values of sound pressure which was further analyzed by loading the sound files into dBSonic for analysis of the psychoacoustic metrics.

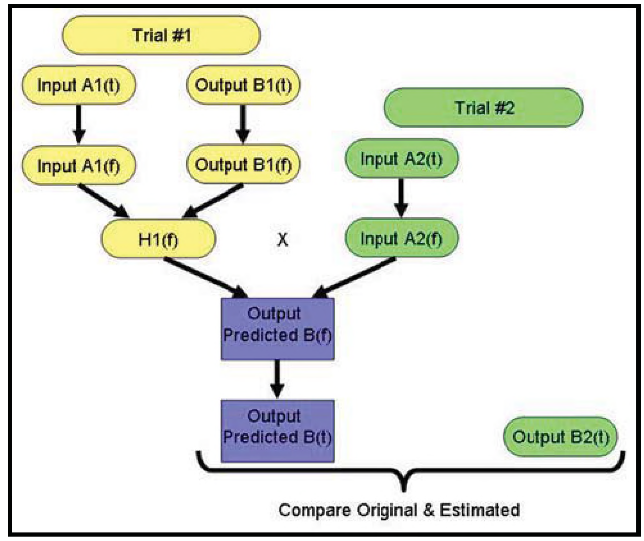


**Figure 13:** *Schematic representation of pressure estimation using Matlab*

## RESULTS & DISCUSSIONS

The following section provides some examples of the calculated frequency response functions obtained in order to present a relationship between the system inputs and outputs as well as how they relate to each other. The ten input signals (all at front driver's side) are as follows:

1. Outside Microphone (Next to the wheel)
2. Acc #1 - Longitudinal Direction (Wheel hub)
3. Acc #1 - Lateral Direction (Wheel hub))
4. Acc #1 - Vertical Direction (Wheel hub)
5. Acc #2 - Longitudinal Direction (Lower A-arm)
6. Acc #2 - Lateral Direction (Lower A-arm)
7. Acc #2 - Vertical Direction (Lower A-arm)
8. Acc #3 – Long. Direction (Top McPherson strut)
9. Acc #3 – Lateral Direction (Top of McPherson strut)
10. Acc #3 - Vertical Direction (Top of McPherson strut)

The system consisted of three microphone outputs from inside of the vehicle:

1. Microphone #1 - Left driver's headrest
2. Microphone #2 - Left passenger's ear
3. Microphone #3 - Right passenger's ear

Testing was done at six different steady speeds. These were all performed with the conditions of the vehicle being driven and motored. As this provided hundreds of different FRFs and coherence functions, discussions in this section will be limited to only provide few of the examples to illustrate the main points. Typical results for two microphone signals are similar to Figure 14 where the top graph represents the frequency response function and the bottom one shows the coherence function which corresponds to the degree of linearity between the two signals in the frequency domain.

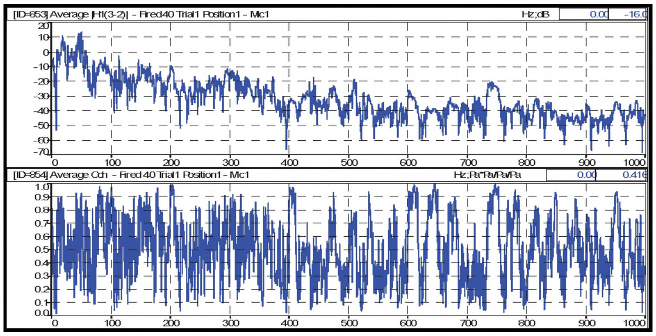

**Figure 14:** *Illustration of Frequency Response Function (Top) and Coherence (Bottom) between Outside Microphone and Passenger's Right Ear for Self-Driven Car at 40 km/hr*

Figure 15 illustrates the FRFs and coherence of the vibration data signal that is correlated to the pressure inside the vehicle. The blue line represents the longitudinal vibration direction, the red line the lateral and the green line represents the vertical direction of the vibration. All three directions generally follow the same trend; however, the vertical direction usually gave slightly higher results then the other two. This is the most important direction since humans are most sensitive to vibration in the vertical direction [14]. However, this cannot be taken as a general rule since at different speeds and at different accelerometer positions, variations are present. When inspecting all the different inputs, one can also see that they are all relatively comparable to each other and that only slight variations are present. It is difficult to make any kind of general statement that applies to all the different inputs as well as all the different speeds simply because there are so many of them.

In general, the coherence levels do not look particularly promising. For the case of low levels of coherence near to zero, this may be caused by some extraneous noise at either the input or the output of the system or that the some other non-correlated input may be passing through the system [12]. In general for automotive applications, vibration data with coherence levels over 70% and acoustic excitation data above 60% respectively, have been shown to be used to successfully estimate interior sound and vibration levels [14]. For this investigation, it was found that the vertical vibration data and noise data taken under the condition of steady speed on a motored dynamometer condition provided the best coherence results.

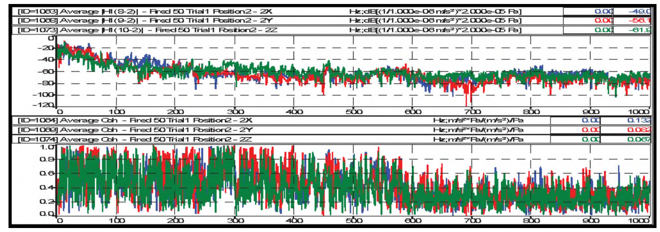

**Figure 15:** *Illustration of Frequency Response Functions (Top) and Coherence (Bottom) between Acc #3 (All three directions and Passenger's Right Ear for Self-Driven Car at 50 km/hr*

To verify the quality of the FRFs, especially with the poor coherence levels, one needs to look at how they can be used to predict pressure levels. Obtained frequency response functions were used to calculate and predict pressure values inside the vehicle based on one of the inputs from outside. One of the trials was used to calculate the FRF from the input and output signals and that FRF would later be applied to one of the input signals from another trial to predict a new value. If one were to look at the original and predicted levels for the case of the motored vehicle at 60 km/hr (Figures 16 & 17), one can see that the predicted pressure levels are very similar. Both microphone and accelerometer stimuli can be used to obtain pressure inside the car; however, we need to be aware that different acceleration directions can give better results when compared to others. This section was used to quickly check the validity of predicted results and not to examine all of them.

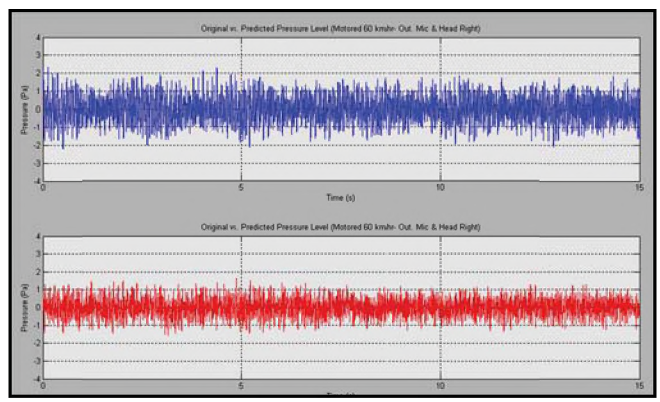

**Figure 16:** *Illustration of Original (Top) and Predicted (Bottom) Pressure Levels for Motored Car at 60 km/hr between Outside Microphone and Passenger's Right Ear*

One can use already predicted values of pressure obtained earlier in order to calculate the psychoacoustic metrics. The following Figures 18 to 21 show agreement between the original and calculated levels for all metrics. At this point, the 60 km/hr motored vehicle is taken arbitrary simply to illustrate this point. At this particular speed, the predicted mean levels of A-weighted sound level are within 2 dB with respect to the original data. It is commonly know that a difference of 3 dB represents the threshold of human perception of change in level. As such, the 2 dB difference represents a variation that is likely indistinguishable to human perception. Roughness and fluctuation strength showed excellent agreement as well.

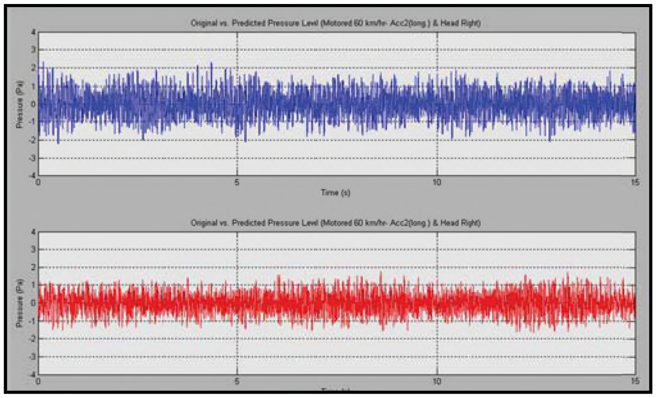

**Figure 17:** *Illustration of Original (Top) and Predicted (Bottom) Pressure Levels for Motored Car at 60 km/hr between Acc #2 in Longitudinal Direction and Passenger's Right Ear*

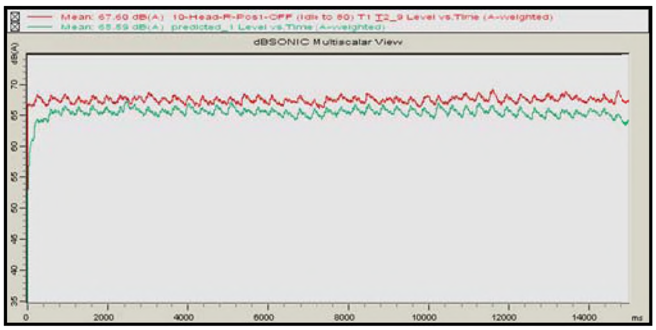


**Figure 18:** *Illustration of Original (Red) and Predicted (Green) A-weighted SPL for Motored Car at 60 km/hr found at Passenger's Right Ear*

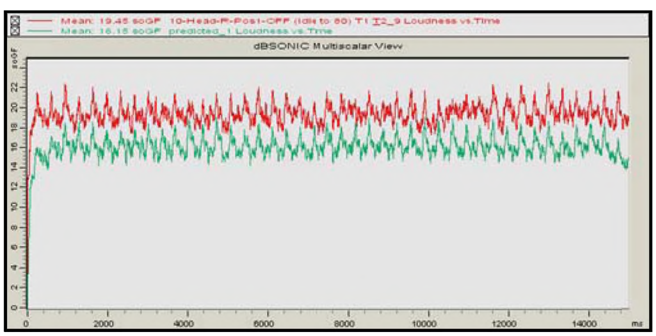


**Figure 19:** *Illustration of Original (Red) and Predicted (Green) Loudness for Motored Car at 60 km/hr found at Passenger's Right Ear*

## CONCLUSIONS

Presently one of the major development issues for the automotive industry is automotive cabin noise. As a result, significant effort is being done to both reduce sound levels as well as improve the sound quality in order to give the consumer a more enjoyable driving environment. Having said this, it is critical to gain an understanding about the different noise sources and their relationship with the receiver points of interest.

An attempt was made to establish a correlation between the noise and vibration measurements from the outside of the vehicle to the noise and psychoacoustic calculations of the noise measured inside the vehicle. This was proven to be possible with some inherent limitations. Direct prediction of the sound quality metrics inside the vehicle from both acceleration and sound pressure observed outside of the vehicle cabin did not show compatible results to the measured data. However, it was proven possible to predict the sound pressure for which the psychoacoustic metrics could be calculated indirectly.

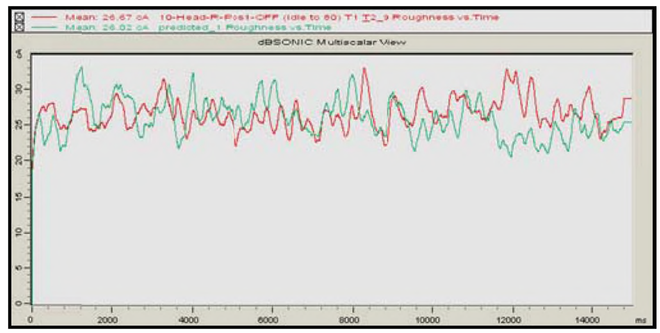


**Figure 20:** *Illustration of Original (Red) and Predicted (Green) Roughness for Motored Car at 60 km/hr found at Passenger's Right Ear*

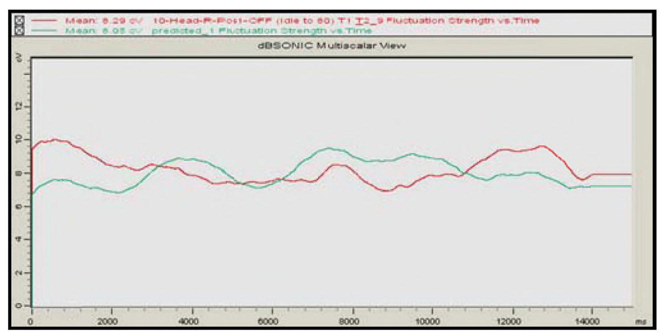


**Figure 21:** *Illustration of Original (Red) and Predicted (Green) Fluctuation Strength for Motored Car at 60 km/hr found at Passenger's Right Ear*

## ACKNOWLEDGMENTS

The authors would like to express their gratitude for the financial support from the AUTO21 Network of Excellence.

Testing was conducted at Application Research Center (ARC) at Canton, Michigan, USA and Ford Motor Company (Windsor Engine Plant) in Windsor. The authors would like to thank the staff at both facilities for their help and expertise.

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# THE COMBINED EFFECTS OF LOW INTENSITY PULSED ULTRASOUND AND HEAT ON BONE CELL MINERALIZATION

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## ABSTRACT

Low Intensity Pulsed UltraSound (LIPUS) has been shown to improve bone fracture healing in *in vivo* animal and human clinical studies. *In vitro*, this improvement has been shown through improved mineralization in bone cells. Low level heat of bone fractures has also been shown to improve healing. Moreover, low level heat has been shown to improve mineralization in bone cell cultures.

The research version of a clinical LIPUS device was used in this study (Exogen® Bone Healing System, Smith & Nephew Inc., Memphis, TN). This study examines the concurrent effects of LIPUS and heat on MC3T3-E1 bone cells. The bone cells were split into four treatment groups: LIPUS, heat, LIPUS + heat, and control. The LIPUS treatment was delivered with the intensity of $I_{SATA}$=30 mW/cm$^2$ at the frequency of $f$=1.5 MHz for 40 minutes each day over 15 days. The heat treatment was applied at 40°C for 40 minutes each day over 15 days. The LIPUS + heat group received the treatments concurrently. Outside of heat treatment the cells were kept at 37 °C.

The groups were tested for calcium mineralization using alizarin red staining and alkaline phosphatase activity in an alkaline phosphatase assay kit. All treatment groups showed statistically significantly improved mineralization when compared to the control cell cultures. Although the LIPUS and LIPUS + heat groups each showed almost a 4 fold increase in mineralization over the control, there was no statistical difference in mineralization between these two groups. Alkaline phosphatase activity was higher in both the LIPUS and the Control groups. Early results suggest that the concurrent effects of LIPUS and heat on MC3T3-E1 bone cells have no additive effect on mineralization.

## RÉSUMÉ

Les ultrasons faible intensité pulsée (LIPUS) a été montré pour améliorer la guérison des fractures osseuses chez les animaux *en vivo* et des études cliniques humaines. Cette amélioration a été démontré par la minéralisation améliorés dans les cellules osseuses *in vitro*. Chaleur de faible niveau de fractures osseuses a également été montré pour améliorer la guérison. Par ailleurs, la chaleur de faible niveau a été montré pour améliorer la minéralisation dans les cultures de cellules osseuses.

La version de recherche d'un appareil clinique LIPUS a été utilisé dans cette étude (Exogen® Bone Healing System, Smith & Nephew Inc., Memphis, TN). Cette étude examine les effets concomitants de LIPUS et de la chaleur sur les cellules osseuses MC3T3-E1. Les cellules osseuses ont été divisés en quatre groupes de traitement: LIPUS, la chaleur, LIPUS + chaleur, et le contrôle. Le traitement LIPUS a été appliquée avec l'intensité de $I_{SATA}$=30 mW/cm$^2$ à la fréquence de $f$=1.5 MHz pendant 40 minutes chaque jour pendant 15 jours. Le traitement thermique a été appliqué à 40 °C pendant 40 minutes chaque jour pendant 15 jours. Le groupe LIPUS + chaleur ont reçu les traitements simultanément. En dehors du traitement thermique des cellules ont été maintenues à 37 °C.

Les groupes ont été testés pour la minéralisation de calcium en utilisant coloration d'alizarine rouges et l'activité phosphatase alcaline d'un kit de test. Tous les groupes de traitement a montré une minéralisation statistiquement significativement amélioré par rapport aux cultures de cellules de contrôle. Bien que les groupes de LIPUS et LIPUS + chaleur chaque montré une augmentation de presque 4 fois dans la minéralisation sur la contrôle, il n'y avait aucune différence significative dans la minéralisation entre ces deux groupes. L'activité phosphatase alcaline a été plus élevée dans les deux groupes de LIPUS et le contrôle. Les premiers résultats suggèrent que les effets simultanés de LIPUS et de la chaleur sur les cellules osseuses MC3T3-E1 n'ont aucun effet additif sur la minéralisation.

## 1. Introduction

LIPUS has been shown to accelerate bone fracture healing. From 1983 to present there have been multiple *in vivo*, *in vitro* and clinical LIPUS studies[1]. There have been several phase-I clinical studies on the effects of LIPUS on bone healing, with up to 40% improvement in bone healing time for fresh fractures (tibia, radius and scaphoid) and up to 85% improvement in bone healing time in the case of non-unions[1-9]. According to Warden et al., LIPUS is now widely available to promote both fresh fracture and non-union bone healing[10].

In 1994 the first therapeutic LIPUS device was approved by the FDA for clinical use with fresh fractures (Exogen® Bone Healing System, Smith & Nephew Inc., Memphis, TN)[11,12]. Further, in 2000, the range of applications increased to include non-unions[12]. Typical LIPUS application is defined as 20 minutes of treatment per day with a 1.5 MHz sine wave ultrasound pulse with intensity (spatial average temporal average) of $I_{SATA}$=30 mW/cm$^2$ repeated at 1kHz with a pulse width of 200μs[1,4]. Due to the prevalence of the Exogen® device, these LIPUS settings are often used as standard treatment settings.

In their review article, Pounder and Harrison suggest that the increase in mechanical strength at the fracture site is due to accelerated mineralization of the fracture callus[4]. This has been well modeled in cell culture experiments [13-16]. With clinical LIPUS settings, Unsworth et al. demonstrated that after 10 days of daily ultrasound stimulation, MC3T3 – E1 mouse osteoblast cells had statistically significant increased mineralization when compared with the control [17]. In addition, they found that with the application of LIPUS the production of alkaline phosphotase (ALP) protein peaked at day 6, where as the control peaked at day 10, with LIPUS treated having statistically significantly greater production of ALP from day 6 onward.

Similar to LIPUS, low levels of heat seem to stimulate bone deposition after injury. Leon et al., while studying the *in vivo* temperature distribution in bone, found that after heating bone to 43°C for 45 minutes, treated 4 times over 21 days, the bone was denser [18]. The study found that the heat treated bone shows a significantly thicker callus. Evidence of improved mineralization was also apparent on a microscopic level. According to Flour et al., a temperature increase to 40°C for 24 hours did not significantly change the viability or proliferation of MC3T3, cells[19]. They suggests the critical temperature for cell culture viability and proliferation is between 42°C and 43°C above which cells will not be viable. Shui et al. tested human bone marrow stromal cells (BMSC) *in vitro* for the effect of heating on mineralization[20]. They found that cells heated for 39-41°C for one hour every 3rd day for 21 and cells heated at 39°C for 96 hours that were measured after 10 days of incubation both showed significant increases in calcium mineralization. Although there is not a large volume of research on the effects of low level heating on bone, the research that has been done indicates that increases in temperature of just a few degrees can significantly increase mineralization of both bone and bone cells.

At intensities in the LIPUS range, ultrasound-induced heat is insignificant and does not seem to be a mechanism of action for enhancing bone mineralization[21,22]. More recently Leskinen et al.[23] tested the effects of heat and ultrasound on an osteosarcoma cell line. The study looked at temporal average power ranging from 200 to 2000 mW ($I_{SATA}$=20-200 mW/cm$^2$, based on a transducer aperture diameter of 25mm) with frequency of 1.035 MHz, pulse repetition frequency of 1 kHz and duty cycle of 20%. Cell signaling associated with improved bone formation increased at temperatures above 48°C and ultrasound power above 400 mW. The heat and ultrasound treatments were not given concurrently. No examples of LIPUS and low level heat (above 37°C and below 42°C) given concurrently have been found in the literature review. Although concurrent application of low level heating and LIPUS has not been tested; the individual treatments seem to improve mineralization in cell cultures.

The hypothesis for this study is that the addition of LIPUS and low level heat will increase mineralization in bone cell cultures.

## 2. Materials and Methods

The experimental protocol was developed in collaboration with the R&D department of Smith & Nephew Inc., Memphis, TN. For more details of the protocol, refer to Weidman (2010)[24].

*LIPUS and Heat Treatment*

*Bench Mark Testing*

The research version of a clinical LIPUS device was used in this study (Exogen® Bone Healing System, Smith & Nephew Inc., Memphis, TN). To establish that the cell line was behaving as previously, the cells were treated with the standard LIPUS treatment for 20 minutes. Two treatment groups were included in this experiment; Control (c) which received no treatment and LIPUS 20 which received 20 minutes of treatment.

*LIPUS and Heat*

For the concurrent treatment, LIPUS was delivered with the intensity of $I_{SATA}$=30 mW/cm$^2$ with an effective radiating area of 3.88 cm$^2$ at the frequency of $f$=1.5 MHz for 40 minutes (LIPUS 40). The heat treatment was applied at 40°C for 40 minutes (H 40). Outside of treatment all groups were kept at 37°C with 5% $CO_2$ concentration.

Four Treatment groups were included in this study: control (C), LIPUS 40, LIPUS 40 + H 40, and H 40. All treatment groups were grown on polystyrene 6 well plates with a well diameter of 3.5 cm. All cells cultures were treated in a 7-day cycle with 5 days of treatment and 2 days off. Samples were taken on days 5, 10 and 15. The experiment was repeated 3 times to account for possible effects due to variations in seeding and cell passage number. The cells samples were taken from passages 4, 5 and 6. Samples were taken out of treatment groups on day 5 of the cycle.

All wells on the 6 well plate were treated simultaneously and driven by the same power source. For the concurrent treatment (LIPUS 40 + H 40), the incubator and water temperature were increased to 40.5 ±0.5 °C prior to treatment; otherwise the set up was left the same as for LIPUS 40. For H 40 the LIPUS device was disconnected from the power source and the incubator and water temperature were increased to 40.5 ±0.5 °C prior to treatment. The control cell culture group remained in the holding incubator.

The schematic in Figure 1 illustrates the experimental set up. The transducer was placed 13 mm below the cell culture well and coupled to the cell culture well using 37°C water. The cell plate was held in place with a fixture above transducer, so that the bottom of the cell plate was always in contact with the water. The water tank was kept inside an incubator to maintain water temperature.

*Cell Culture Technique*

The cells were cultured in an ascorbic acid free Minimum Essential Medium Alpha (Gibco® by Invitrogen Carlsbad, California) supplemented with 10% Fetal Bovine Serum and 1% antibiotics. The cells were seeded at approximately $10^5$ cells/ml. At the seeding stage, 50µg/ml of ascorbic acid and 3mM/ml of β-glycerol phosphate were added to the cell culture media as sources of nutrients to the cells. A total of 2ml of media was added to each well. In all experiments cells were seeded 72 hours prior to treatment. This allowed the cells time to proliferate, adhere to the well plate surface.

*Staining for Mineralization*

To prepare the cell culture samples for mineralization, the media was removed from the wells, the cultures were washed 3 times with $CaCl_2$- and $MgCl_2$-free PBS. The culture was then fixed by adding 1ml of 10% formalin at room temperature (20°C) (Sigma Aldrich Inc., Oakville, Ontario) to each well. Once fixed, the wells were rinsed and then stained with 1ml of 1 mg/ml Alizarin red (pH 4.2). The cultures were incubated at room temperature for 20 minutes at 20°C. The cultures were then rinsed 3 more times. The fixed and stained cell cultures were then left to dry for 24 hours.

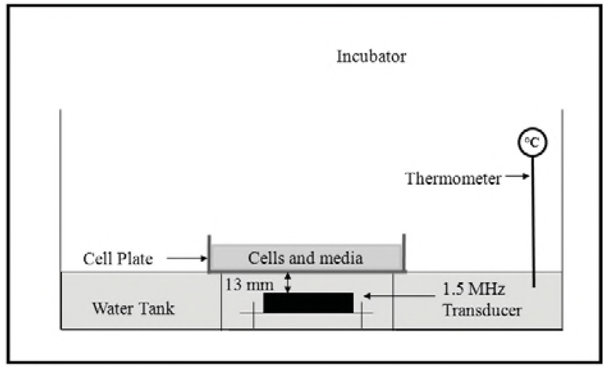


**Figure 1: Experimental set up.**

To quantify mineralization, the cell cultures were de-stained by adding 1 ml of room temperature 5% perchloric acid to each well. The perchloric acid rehydrated and dissolved the culture stain for 23hours. After 23 hours of incubation at room temperature, five samples of the dissolved stain were taken from each well to measure optical absorbance.

To quantify the degree of staining, the 96 well plate was put through a Thermo Lab Systems Multiskan Ascent plate reader with Ascent software (Thermo Fischer, Franklin, MA) to measure absorbance. Absorbance for each well was read at 405 nm. The average of 5 mini-wells was considered the absorbance for that sample.

*Alkaline Phosphatase Activity*

The alkaline phosphatase (ALP) activity was measured using the QuantiChrom™ Alkaline Phosphatase Assay Kit (DALP-250) available from BioAssay Systems. Following the kit protocol, the cultures were washed 3 times with $CaCl_2$- and $MgCl_2$-free PBS. The culture was lysed in 0.5 mL 0.2% Triton X-100 in distilled water for 20 min. The working solution was prepared with 200 µL of the assay buffer, 5 µL of Mg Acetate and 2 µL of pNPP. A 5µL volume of the supernatant was mixed with 195 µL of the working solution. The solution was immediately put into a plate reader and optical density measurements were taken at 405 nm at 0 and 4 min. ALP measurements were taken on days 2, 4, 6 and 9. The tests were repeated 3 times. The protein activities were normalized using a Bradford assay.

*Statistic*

The samples were compared to the control treatment using a single sided student's *t*-test.

## 3. Results

*Bench Mark Testing*

When initially testing LIPUS 20 treatment against the control, the results indicated statistically significant differentiation by day 10 (see Table 1). Although these results are similar to previously published data[17], the cell culture mineralization was weak. To improve mineralization, the LIPUS treatment time was increased from 20 to 40 minutes.

*Combined Treatment Effect*

Using LIPUS 40 and H 40, by the fifth day after treatment, all cell groups showed significant mineralization when measured against day 0 cells (see **Error! Reference source not found.**). The greater degree of mineralization suggests that the cells have begun the cycle of differentiation[25]. This occurred in all cell culture treatment groups over all three trials.

| | P values |
|---|---|
| Day 5 | 0.0669 |
| Day 10 | 0.0074 |
| Day 15 | 0.0022 |

**Table 1: The statistical treatment effect for LIPUS 20 treatment. The P value represents the probability that the mean mineralization of the treatment is greater than that of the control. Statistical difference reached by day 10. P values less than 0.05 are considered statistically significant.**

By day 15, the mean optical absorbance of LIPUS 40 and LIPUS 40 + H 40 has increased almost 6 fold over the Control and H 40 samples (see Figure 2). H 40 showed an increase in mineralization of 1.2 fold over the Control, which is comparable to published values[26]. The results indicate that LIPUS 40, LIPUS 40 + H 40, and H 40 treatment groups all show statistically significantly improved mineralization when compared to the Control (see Table 2). The error bars for the LIPUS 40 and LIPUS 40 + H 40 treatment groups are much larger than the error for the H 40 and the Control treatment groups. In addition, there was no statistically significant difference in mineralization between the LIPUS 40 and the LIPUS 40 + H 40 treatments.

| | LIPUS 40 | LIPUS 40 + H 40 | H 40 |
|---|---|---|---|
| Day 5 | 0.0554 | 0.3019 | 0.13 |
| Day 10 | 0.457 | 0.567 | 0.0034 |
| Day 15 | 0.0003 | 0.0004 | 0.0031 |

**Table 2: Treatment effect statistics – P values. The P value represents the probability that the mean mineralization of the treatment is greater than that of the control. All day 5 measurements are statistically significantly greater than day 0 (P=0.0001). P<0.05 is statistically significant.**

When the treatments are compared within each group, it is clear that there is an increase in mineralization over time (see Figure 2). Both of the LIPUS 40 and the LIPUS 40 + H 40 treatment groups showed distinct mineralization between days 10 and 15. This trend indicates that mineralization seems to begin in this window of time.

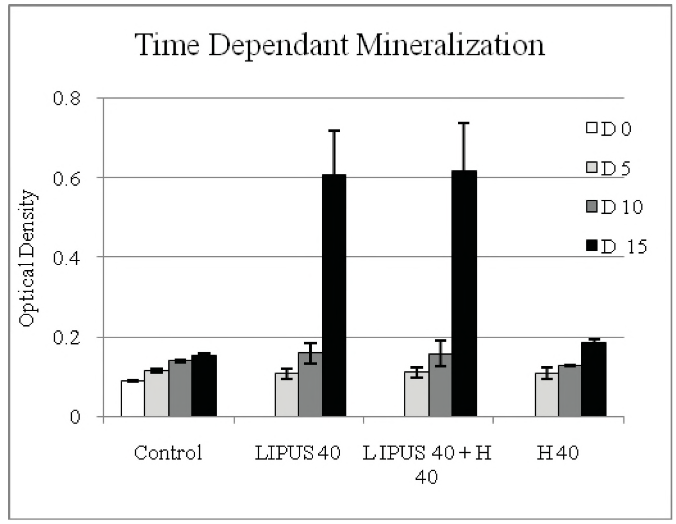


**Figure 2: Comparison of treatments over time. Error bar indicates a standard error of 18 measurements.**

Alkaline phosphatase is an indicator of the stage of cell differentiation. A peak in ALP activity is a sign that the cells are moving through this early stage of differentiation. Generally this occurs between the second and tenth day of cell differentiation. In this series of experiments the cell cultures treated with LIPUS 40 show a distinct peak of ALP activity on day 6, with a decrease on day 9. The control cell culture does not have a clear peak in this range, however the activity is increasing throughout the test period. The cultures treated with LIPUS 40 + H 40 and H40, also continue to increase over the test period however the rates are lower that the control cell cultures.

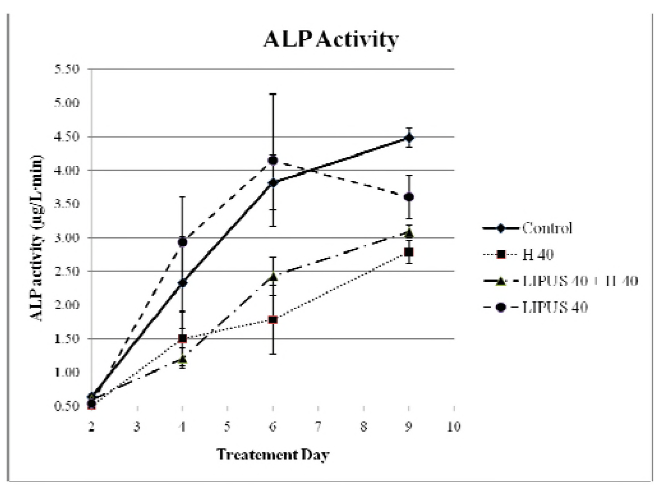


**Figure 3: Alkaline Phosphatase (ALP) activity.**

## 4. Discussion

Many adjuvant therapies have been tested with ultrasound; however the combination of low level heating and LIPUS has not been studied. The addition of heat to ultrasound is potentially a low cost and non-invasive technique to improve fracture healing. From practical point of view, combining the two therapies would be quite attractive since at the interface between bone and soft tissue, the ultrasound alone can be used as a non-invasive local heat source. The importance of the individual and combined therapies is that they reduce the time for fractures to heal and increase the functional properties of bone. Both early healing and improved bone function are associated with mineralization.

The results of the experiment showed that there was a 6 fold increase in mineralization for the LIPUS 40 treatment group when compared to the control. Based on published data, the result for the LIPUS 40 was expected. Leung et al. showed a 4 fold increase in mineralization after 4 weeks of ultrasound treatment when using human periosteal cells[27]. The H 40 treatment group also showed an expected increase of 1.2 fold in mineralization over the control. Shui et al, using an osteosarcoma derived cell line, showed an increase in mineralization of 1.25 fold when the cell cultures were heated to 39°C and 1.69 fold when the cell line were heated to 41°C[20]. An additive effect for the LIPUS 40 + H 40 group might be expected to be in the range of a 4.2 fold increase in mineralization. However, the LIPUS 40 + H 40 showed only a 4% increase over the LIPUS 40 treatment group. Due to the large variation of mineralization in the samples, this increase was not statistically significant. Therefore the outcome of our study shows no additive effect in the combined treatment group.

The results of the ALP tests show that LIPUS 40 has a peak in activity prior to the control group which continues to rise. Interestingly, the LIPUS 40 + H 40 group did not show a peak at all between day 2 and day 9. It is possible that the peak activity was missed or that it had not occurred yet. The tests did not conclusively show that the combined treatment of heat and ultrasound could improve the onset of cell differentiation.

There are a couple of possibilities to explain why there was no additive effect found for the LIPUS 40 + H 40 treatment group. It is possible that the mechanisms of action of each treatment may have different onset timing, the mechanisms of action of the treatments may not complement each other, and finally the test method may not be sensitive enough to detect a difference between the treatment groups.

Although the exact mechanisms are unknown, certain cellular level responses to ultrasound treatment have been shown to be repeatable. Increased mineralization is a distinct repeatable outcome from the application of ultrasound[4]. The mechanisms of action for ultrasound are thought to be the mechano-sensitization of cell integrins. According to Pounder et al. surface integrins mediate the mechanical signal on the cell surface and cause a cascade of changes throughout the cell[4]. Integrins are a large family of cell adhesion molecules that mediate interactions between the extracellular environment and the cytoplasm[28]. These integrins provide a physical link between the cytoskeleton and the extracellular matrix. According to Tang et al.[29], these integrins are stimulated by the ultrasound signal from the surrounding matrix, and this stimulation causes the integrins to start a cascade of change in the cell causing a series of subsequent expressions eventually causing the cells to express calcium and the collagen matrix to mineralize. The mechano-sensitive integrins stimulation caused by the ultrasound waves is theorized to be the mechanism behind ultrasound-cell interaction[29,30].

Although there are multiple examples of the temperature dependence of bone growth, the mechanisms of action are even more elusive than ultrasound. Shui and Scutt suggest that most likely the mechanism of action is related to the expression of Heat Shock Proteins (HSP); where HSP are molecular chaperones associated with cell survival after an insult[20]. Shui suggests that HSP47 is involved with collagen synthesis and the expression of HSP47 is more likely to be induced in the presence of Transforming Growth Factor (TGF-β1), where TGF-β1 is released by the addition of heat. According to Naruse et al., LIPUS does not stimulate the expression of TGF- β1 in MC3T3 cells[31]. However, ultrasound does stimulate this growth factor in other cell lines or at higher intensities[32,33]. Calderwood and Asea[34] suggest that when cells are exposed to temperatures over 40°C the production or Cyclo-oxygenase 2 (COX-2) and prostaglandin (PGE2) will increase.

The combination of LIPUS 40 + H 40 concurrently may prove not to be additive. Although heat induces HSP and ultrasound induces mechano-sensitivity, both energy sources have a downstream effect of increasing COX-2 and PGE2. It is possible that these expressions are maximized with one energy source and cannot be expressed more with the addition of a second source.

It is also possible that the additive effect of LIPUS 40 + H 40 was missed simply because the testing was not sensitive enough. From day 15 measurements, the standard error in light absorbance of the LIPUS 40 and LIPUS 40 + H 40 treatment groups is 0.1 with an average absorbance of 0.6. H 40 treatment produced an error 10 times smaller than either of LIPUS 40 or LIPUS 40 + H 40. With an error of 0.01 and an average absorbance of approximately 0.2, the error of both LIPUS groups is almost as large as the total absorbance of the H 40 group.

## 5. Conclusion and Future Work

There was no statistically significant difference in mineralization between the LIPUS 40 and the LIPUS 40 + H 40. It can be seen from the cumulative results that the onset of mineralization is between days 10 and 15.

Refining the experimental protocol may provide an opportunity to reduce error in the experiment. Allowing the cells to remain in culture beyond 15 days may provide a method to reduce the effect of uneven seeding. It may be possible that, if the cells are left for longer in culture, the mineral expressions may reach a steady state. The comparison of mineralization once the cultures have reached a steady state of mineralization may reduce the large errors (especially in the LIPUS 40 and LIPUS 40 + H 40 treatment groups) so that subtle changes due to the addition of LIPUS and heat may become evident. It addition, it may be possible that increasing the number of cells initially seeded may reduce the time needed for the culture to proliferate, therefore reducing the variation in initial time of proliferation.

## 6. Acknowledgements

This work was partially supported by the Ryerson University Dean's Start-up Fund that was made available to Dr. Tavakkoli. We would like to thank Dr. Debora Foster for providing laboratory equipment for this study. We would also like to thank Smith & Nephew Inc., Memphis, TN, for providing technical support and a research device.

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# Acoustics Standards Activity in Canada - 2011

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## ABSTRACT

This article is an update for 2011 of Acoustics Standards activities in Canada, It lays out the new organisation of Canadian activities in developing, reviewing and reporting on acoustical standards, both in Canada and around the world.

## RÉSUMÉ

Cet article est une mise à jour des activités de normalisation en acoustique au Canada pour 2011.

## 1. INTRODUCTION

Canadian acoustical standards activity in Canada has had large changes over the last few years and 2011 has seen the culmination of all this activity.

In 2009 CSA announced that they were going to drop or severely scale back their Z107 technical committee which since the 70's had been the main acoustical standards group in Canada. They offered the Canadian Acoustical Association the opportunity to take over standard Z107.10, which had become their main way of endorsing acoustical standards from around the world. The board of directors unanimously agreed to form a new Acoustical Standards Committee and it held its first meeting in 2009 at the CAA conference in October. The CAA was actually formed in 1963 As the Canadian Committee on Acoustics, intended to organise acoustical standards in Canada. The CAA has a long history of involvement with acoustical standards, including hosting Z107 at their annual meetings.

The CSA re-examined the acoustical standards they had and decided that they would like to continue to look after occupational noise and vibration standards, bringing the former Z107 standards across to their TC 94.2 committee which looked after a single standard on hearing protectors. The new CSA Technical Committee on Occupational Hearing Conservation S304 was formed, with the following mandate:

- Hearing conservation management systems;
- Workplace noise and vibration measurements;
- Determination, measurement, and assessment of occupational exposure to noise and vibration;
- Strategies for reducing exposure to noise and vibration in the workplace.

This committee held its first meeting in May 2010 and this was organised as a joint meeting of both the CSA and CAA committees. Since that time both committees have met jointly in May at the CSA headquarters and in October as part of the CAA Acoustics Week in Canada conference.

## 2. CSA Z1007: Management of Hearing Conservation in the Workplace – Jeff Goldberg

CAALL-OSH, the Occupational Safety and Health Committee of the Canadian Association of Administrators of Labour Legislation, agreed to fund the development of a new Canadian standard on Hearing Conservation Management. This would be part of CSA´s OHS Management systems standards series. It would encompass prevention of occupational hearing loss, control of noise in the working environment and be applicable to all occupational sectors and to all workers and occupations. This work was undertaken by SC1 chaired by Jeff Goldberg, and has just completed the first draft of the standard.

## 3. CSA Z94.2 - Hearing Protection Devices - Performance, Selection, Care, and Use – Alberto Behar

S304 is still responsible for the Z94.2 standard on Hearing Protection. For many years this standard has advocated the use of type A,B, and C hearing protectors. While a good and simple system, this categorization of hearing protectors has not become widely used, primarily because most protectors are also marketed in the US, where by law they must be labeled with the protector's NRR rating, and this is the system most commonly used by Canadians because it is more visible.

The NRR system was put in place in 1974, and has not changed since that time. Meanwhile, expert opinion has come to realize that there are severe flaws in the system. The primary problem is that the number shown grossly overstates the actual protection provided in the workplace. Z94.2 is advocating the NIOSH approach to derating the NRR ratings. For example an NRR rating of 30 for a slow recovery foam earplug actually reduces the sound level at the ear by about 8 dBA in practice compared to the sound level outside the protector.

ANSI in the US recognized the problems and developed new more representative subject fit testing methods but so far the EPA has not adopted them, instead proposing a dual percentile label which is rather complicated to use. At this point the EPA has not come out with a final solution and this makes it difficult for the CSA writing group to come to a conclusion, although otherwise they have drafted a new version of the standard which is nearly ready for balloting.

## 4. CSA Z107.56

The most widely used of the Z107 series, 56 covers the measurement of occupational noise exposure and was the first standard to do so. A new version is now being proposed which will extend its scope to cover noise exposure under headsets, which is a serious concern for pilots, call centre operators, drive through attendants and many others. The new approach has been described in References 1 and 2 and encompasses measurements with probe microphones in real ears, measurements using mannequins and artificial ears and a new calculation method using the NR of the headset and the measured sound level outside the headset.

The use of probe microphones and mannequins is covered by Australian and international standards, to which the new version refers. However the calculation method is new. It is intended to be a low cost initial assessment compared to the other systems. If the calculation method shows a possible concern it may well prove cheaper and certainly more effective to reduce the noise exposure in many cases than to undertake the more advanced measurements.

## 5. CSA Z107.58

This standard describes in one location all that Canadians need to know to navigate the variety of standards, codes and regulations which make up the system whereby the sound produced by machinery is documented and available to prospective buyers and users. Health Canada has recently recommended its use by Canadian industry and a new version is expected which will update the constantly changing standards on which the system is based. This system can help industry to buy quiet equipment and help manufacturers provide prospective purchasers with accurate information about sound levels produced by their equipment. Reference 3 provides more detailed information about the standard.

## 6. CSA TSC on Wind Turbines - Acoustic Noise Measurement – Brian Howe

This subcommittee of the CSA Technical Committee on Wind Turbines helped this group adopt IEC 61400 Part 11: Acoustic Noise Measurement Techniques, for use in Canada. This provides an internationally recognized approach to measuring and characterizing the noise produced by wind turbines, which can then be used to assess the expected community impact.

## 7. CAA Standard 101 (formerly CSA Z107.10)

At this point the only standard under the auspices of the CAA, this is a compendium of Canadian, US and International standards of interest to Canadians. It provides a short description of each standard and any items that should be borne in mind when using them within the Canadian context. To ensure that it is representative, the committee is currently developing voting procedures and memebership guidelines to recommend to the board.

Look for this standard sometime in the coming year on the CAA website. It provides one of the best reviews of acoustical standards available anywhere and indicates the standards considered most useful to Canada. The intent is that this document will be the entry point for Canadians and others needing to understand acoustical standards. To ensure that it is complete we invite any and all CAA members to propose for consideration other standards which should be included in the document. Simply send a recommendation and brief write-up to my attention as chair.

We expect the standard will be freely downloadable and provide links to each standard it discusses for those requiring more information. We will be looking for sponsors for this website when it appears.

## 8. Standards Council Steering Committees

The Standards Council of Canada has steering committees involved with major international standards groups, including:

ISO TC 43 SC2, Building Acoustics – David Quirt – This group Includes both the ASTM and ISO building acoustics groups and tries to advise on which group provides the best standards for Canada.

IEC/TC 29: Electroacoustics, Lixue Wu. – This group has provided Canadian input into acoustical instrumentation for decades and is well respected internationally.

ISO TC43 (Acoustics) and TC43(1)(Noise) - Stephen Keith – This group covers the majority of international acoustics standards.

ISO Vibration Standards ISO 2631, ISO/TC108/SC4 – Tony Brammer – For years Tony has been the chair of ISO 2631 and provided Canadian input to that body, as well as helping Canadians understand the effect of vibration on people.

These groups meet under the auspices of the CAA Standards Committee to coordinate their activities and report the results.

For those wishing more detailed information about any of these many activities, the CAA website has copies of committee meeting minutes which cover the topics in considerably more detail than is possible in a review article and the reader is referred to this resource.

## REFERENCES


1. Alberto Behar, Christian Giguère, Tim Kelsall, Measurement of noise exposure from headsets, NOISE-CON 2008, 2008 July 28-31.

2. Alberto Behar, Christian Giguère, Tim Kelsall, CSA Appendix on Measurement of Noise Exposure from Headsets, Canadian Acoustics, September 2008.

3. Stephen Keith, Stephen Bly, Tim Kelsall, A preview of the Draft CSA Guideline – Noise Emission Declarations for Machinery, Canadian Acoustics, Volume 29, No. 3, September, 2001.

***Editor's Note:*** The following paper was orginally published in the March 2011 issue, but it was laid out improperly. We apologize for this oversight and the full paper is reproduced below.

# REVERBERATION MEASUREMENT AND PREDICTION IN GYMNASIA WITH NON-UNIFORMLY DISTRIBUTED ABSORPTION; THE IMPORTANCE OF DIFFUSION

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## ABSTRACT

As part of a performance verification exercise reverberation times (RT) were measured in several newly constructed school gymnasia, rectangular in plan with two variations in room size, all with similar finishes and constructions. Due to architectural constraints, the rooms have acoustically hard finishes below a height of 3 m. The room finishes are primarily acoustically reflective with the exception of continuous bands of absorptive upper wall paneling around the full perimeter of the rooms (exposed unpainted Tectum over mineral fibre insulation) and painted acoustic metal deck ceilings (fiberglass insulation in the perforated deck flutes). The initial RT measurements exceeded the design targets. Modeling using ODEON room acoustics prediction software was conducted to determine the quantity and placement of additional absorption required to bring the RT into compliance. After installation of an additional continuous band of absorptive paneling in the rooms at a height below the existing panels, the RT were re-measured. The mid-band average RT increased, with a 0.5 sec RT increase at 1000 Hz in one room and a 1 sec RT increase at 1000 Hz in another. Further investigation lead to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results. RT were subsequently re-measured under 5 different conditions; an empty gym, addition of 5 people, and 3 levels of diffusion. Diffusion was varied by adding sheets of plywood (5, 10, 15 sheets) leaned against posts or each other. The addition of as few as 5 people or 5 plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions, with between a 0.6 sec and 1 sec reduction observed in the mid-band average RT from the empty condition.

## RÉSUMÉ

Dans le cadre d'un exercice de vérification des performances, les temps de réverbération (RT) ont été mesurés dans plusieurs gymnases d'école nouvellement construits d'un plan rectangulaire, avec deux variations de taille de pièce, mais tous avec des finitions et de construction semblables. En raison de contraintes architecturales, les salles n'ont aucune finition acoustiquement absorbante au-dessous d'une taille de 3 M. Les finitions de pièce sont principalement acoustiquement réfléchissantes, à l'exception des bandes continues du panneautage absorbant de mur supérieur autour du périmètre complet des salles (Tectum exposé non peint sur l'isolation de fibre minérale) et des plafonds peints de plate-forme en métal acoustique (isolation de fibre de verre dans les cannelures perforées de plate-forme). Les mesures RT initiales ont excédé les exigences de performance. La modélisation en utilisant le logiciel de prévision d'acoustique des locaux d'ODEON a été fait afin de déterminer la quantité et le placement d'absorption supplémentaire exigés pour introduire le RT dans la conformité. Après l'installation d'une autre bande continue du panneautage absorbant au-dessous des panneaux existants, les RT ont été remesurés et se sont trouvés plus hauts de 0.5 sec à la bande 1000 Hz dans une salle et 1 sec plus haute dans l'autre. Plus de recherche a mené à l'hypothèse qu'un champ acoustique insuffisamment diffus et des modes d'onde stationnaire non interrompus dans la partie non traitée au bas de la salle ont contribué aux résultats inattendus. Les RT ont été remesurés dans 5 conditions différentes; un gymnase vide, avec l'addition de 5 personnes et avec 3 niveaux de diffusion. La diffusion a été variée en ajoutant des feuilles de contreplaqué (5, 10 et 15 feuilles) appuyé contre les poteaux ou l'un à l'autre. L'addition de seulement 5 personnes ou de 5 feuilles de contreplaqué a réduit les RT mesurés, entre 0.6 sec et 1 sec dans la moyenne des mi-fréquences en comparaison de la salle vide, un résultat plus près des predictions modélisées.

## 1. INTRODUCTION

School gymnasia present several acoustical challenges as the rooms must support variety of uses, mainly athletic instruction, practice and competition, school and community gatherings, as well as both drama and music performances. Excess noise levels and reverberation are common concerns for these facilities. However considerations such as user safety, surface durability and impact resistance, ease of maintenance and clean-ability often dictate the application of acoustically reflective finishes in the occupied portion of the room. Further, the room contain parallel and acoustically reflective floors, ceilings, and lower wall surfaces.

Previous research [1] has indicated that reverberation times (RT) between 1.5 and 2 seconds across the speech frequency range are favourable for gymnasia in order to preserve a sense of excitement for sporting activities and liveliness for musical performances while not significantly compromising speech intelligibility which is strongly dependent on reverberation time and background noise levels.

This paper documents the results of RT measurements conducted in several newly constructed school gymnasia as part of a performance verification exercise for the builder. These gymnasia are located in Alberta where current government design standards [2] stipulate that RT in a typical unoccupied gym not exceed 2.0 sec averaged over the frequency range of 500 to 2000 Hz.

The gymnasia were built with acoustical finishes described as acceptable in the Alberta Infrastructure design guidelines [2], however the initial RT measurements did not meet the design target. Furthermore, the mid-band average RT measured after the installation of additional acoustically absorptive treatment were found to be higher, with a 0.5 sec RT increase at 1000 Hz in one room and a 1 sec RT increase at 1000 Hz in another, contrary to intuition and the predictions from geometric room acoustical modeling.

It was noted that the presence of a minimal amount of solid objects on the floor during some of the measurement sessions appeared to significantly influence the measured RT, with a 1.2 sec RT decrease at 1000 Hz in one room and a 1.4 sec RT decrease at 1000 Hz in another. This led to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results.

RT were subsequently re-measured under 5 different conditions; an empty gym, addition of 5 people, and 3 levels of diffusion. Diffusion was varied in a simple manner by adding sheets of plywood (5, 10, 15 sheets) leaned against posts or each other. The addition of as few as 5 people or 5 plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions. The results of the above investigations are presented in this paper.

## 2. ROOM DESCRIPTIONS

Eighteen new elementary schools, nine in Calgary and nine in Edmonton, were constructed for the Alberta Government in a Public Private Partnership P3 arrangement. Two of the seven basic school designs were chosen by the builder for acoustical testing. Two of the schools were in Calgary and the other two were in Edmonton.

The measured gymnasia were rectangular in plan with two different room sizes: Type A, 27.8 m x 18.5 m, slightly sloped ceilings 9.3 m to 9.6 m above finished floor (AFF); Type B 24.0 m x 18.0 m, ceilings 9.1 to 9.5 m AFF. The finishes were painted concrete block walls to 3 m above a cushioned wood floor and painted 2-layer 16 mm thick abuse-resistant gypsum board walls to the underside of a painted acoustic metal deck ceiling. According to an acoustical lab test report provided by the metal roof deck manufacturer, the acoustic deck has a Noise Reduction Coefficient (NRC) of 0.75 with a pronounced peak in the mid-band absorption.

Initially, two 1.2 m high continuous bands of exposed unpainted Tectum/mineral fibre paneling (38 mm mineral fibre behind 25 mm Tectum, edges concealed with wood trim) extended around the full perimeter of the rooms on the upper walls, approximately 222 $m^2$ and 202 $m^2$ in the Type A and B gymnasia respectively, providing roughly 25% wall coverage. The bottoms of the panels were approximately 4.5 m AFF in the Type B gyms and approximately 5.5 m AFF in the Type A gyms. According to the panel supplier the tectum/mineral fibre panels have an NRC rating of 0.85 with significant mid-frequency absorption.

## 3. METHODOLOGY AND LIMITATIONS

A tripod-mounted Brüel & Kjaer 2270 Precision Real Time Sound Level Analyzer equipped with a Brüel & Kjaer 4189 microphone and Brüel & Kjaer UA 1650 windscreen and version 3.2 of the BZ7227 Reverberation Time software was used to record, archive and evaluate the RT measurements. Microphone height was approximately 1.8 m AFF.

Sound decays were measured at a minimum of 5 locations in the rooms with the exception of the first set of measurements in Gym A-1 and Gym B-1. During these initial survey measurements decays were measured at 3 positions in Gym A-1 and at 4 positions in Gym B-2. Measurement positions were consistent (within ~0.5 m) between repeated measurement sessions in the same gymnasium. Standard deviation in RT between measurement positions did not generally exceed 0.1 sec in the 250 Hz to 4000 Hz range. However the standard deviation in RT between measurement positions was as high as 0.14 sec at 125 Hz and 0.12 sec at 1000 Hz in some instances.

Sound impulses were generated from large diameter balloon bursts and the decays measured. In some instances the measurements were repeated with decays generated with interrupted pink noise played over a JBL Eon Power 15 amplified speaker. Good agreement was found between the two methods with the measured mid-band average RT generally within 0.1 sec for the same room using the two methods. During the final measurement session with added diffusion only large diameter balloon burst impulses were used. Reported RT are those measured with large diameter balloon burst impulses.

Background noise measurements were taken during each measurement session and found to not exceed RC 35 (N) with the exception of the initial measurements in Gym A-1 which were taken before the HVAC system air-balancing was completed and met an RC 46 (HF). In all cases sufficient sound energy was generated in the frequencies of concern for the decays that the background sound levels were not a factor in the RT measurements.

## 4. RESULTS & MODELLING

The initial RT measurements (see Figure 1) did not meet the design target and were surprising in that the mid-band average RT in the slightly smaller Type B gym were 1.2 sec higher than those measured in the Type A gym. These measured times were higher than expected considering the extent of and the manufacturer-claimed mid-band sound absorption of the acoustic deck and acoustic panels.

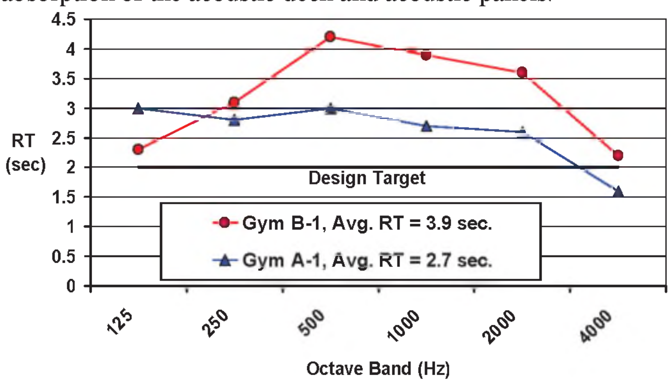


**Figure 1. Initial measured gymnasia RT with ~25% wall panel coverage.**

The acoustical treatments in this Type B gym were inspected and no problems or defects were apparent. The acoustic deck perforations were not sealed with paint and the flutes had fibrous batt insulation in them. The Tectum appeared to be installed as per the manufacturer's recommendations; the Tectum was porous and mineral fibre was present behind the Tectum.

The RT were re-measured in this room. With the room empty (except for the scissor lift used for the acoustic treatment inspection) the re-measured RT were lower than the initial measurements yet still above the performance requirement (see Figure 2).

A lack of adequate absorption was presumed and the two basic variations of gymnasia (Type A & B) were modelled using ODEON room acoustics prediction software to determine the quantity and placement of additional absorption required to bring the RT into compliance. ODEON is based on prediction algorithms (image-source method, ray-tracing and ray-radiosity) that account for scattering due to surface roughness and diffraction. A reflection-based scattering method is used that accounts for frequency-dependent scattering [3]. Scattering coefficients were chosen according to ODEON guidelines [4].

Air temperature and humidity readings recorded during the gymnasia RT measurements were used in the modelling (Type A Gym: 20 °C, 37% RH, Type B Gym: 20 °C, 38% RH).

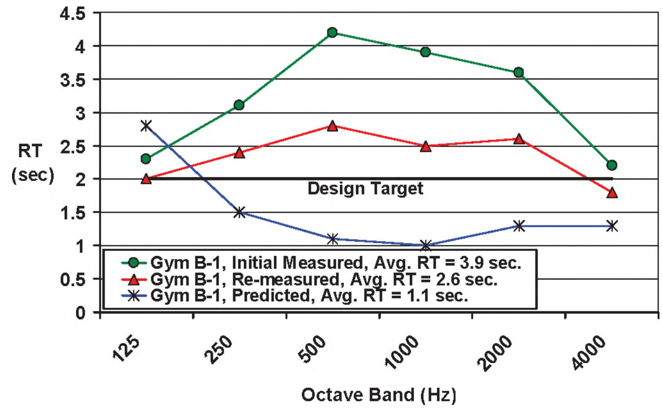


**Figure 2. Initial (circles) and re-measured (triangles) RT in Gym B-1 with ~25% wall panel coverage. Predicted RT (asterisks) also shown.**

As explained by Cox and D'Antonio [5], the accuracy of geometric room acoustic modelling software is limited by the validity of the input data, namely the accuracy of the modelled room geometry, surface sound absorption and scattering coefficients. In this case the geometry for the gymnasia is not complex. Furthermore, with the exception of the acoustic deck and Tectum panels the absorption coefficients for the various room materials are fairly well established in literature. This does not mean these values are infallible.

Recent literature by Cox and D'Antonio [5] and Sauro and Mange [6] describe how there can be significant uncertainty in absorption coefficients even for common materials due to factors such as sample size, edge effect (sound diffraction at sample edges), and variations in diffusion and sample mounting conditions between various testing labs. Cox and D'Antonio recognize that with practice experienced acoustical modellers gain an understanding of how absorption coefficients vary between lab test data and real rooms. Uncertainties in absorption coefficients are dealt with by adjusting absorption coefficients used in the modelling based on measured RT with repeated use of surface treatments on various projects over time. This is relevant to this study in that both acoustic deck and Tectum panels have been used in enough projects to establish that they provide at least some absorption in the critical mid frequency bands.

As the predicted RT with the acoustic treatment manufacturers' absorption data were significantly below the measured values, the absorption coefficients in the models were 'calibrated' so that the predictions better matched the measured RT. The calculations indicated that an additional 148 m$^2$ of panels were required in the Type A gyms and an additional 96 m$^2$ of panels were required in Type B gyms.
A third continuous 1.2 m high band of panels approximately 111 m$^2$ in area was installed in the Type A gymnasia at a height below the existing panels (bottom of panels constrained to a height approximately 3.4 m AFF). The resulting wall panel coverage in the Type A gymnasia was approximately 40%. In the Type B gymnasia a third

continuous band of panels approximately 76 m$^2$ to 101 m$^2$ in area (depending on interference with existing perimeter radiation cabinets) was installed at a height below the existing panels (bottom of panels approximately 3 m AFF). The resulting wall panel coverage in the Type B gymnasia was in the 35% to 40% range.

The RT were re-measured and the mid-band average RT were found to be higher due to primarily to the higher RT at 1000 Hz, contrary to intuition and the predictions (see Figures 3, 4 & 5). The measurement results seemed to indicate a greater difference from the predicted RT than could be explained by invalid absorption and/or scattering coefficients. Subsequent adjustments to these model inputs confirmed this.

The commissioning agents for the project had their independent acoustical consultant conduct RT measurements in Gym B-2 [7]. As can be seen in Figure 5 the results of these measurements were significantly higher, a mid-band average RT of 2.8 sec vs. 2.1 sec.

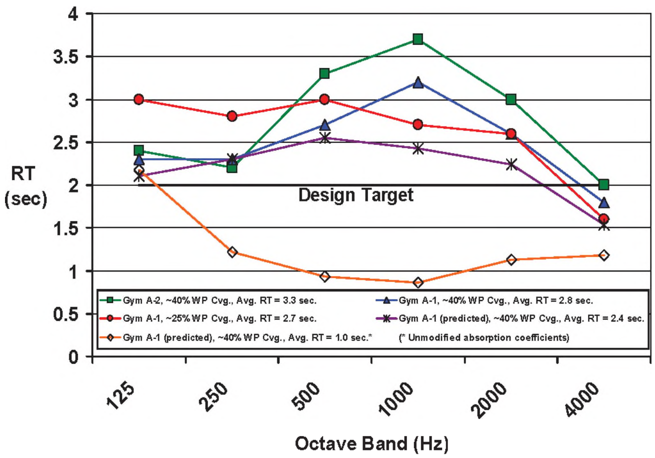


**Figure 3. Comparison of initial, re-measured and predicted RT in two Type A gymnasia with varying wall panel coverage. Squares: Gym A-2, ~40% wall panel coverage. Circles: Gym A-1, ~25% wall panel coverage. Triangles: Gym A-1, ~40% wall panel coverage. Asterisks: predicted RT with modified acoustic treatment absorption coefficients. Diamonds: predicted RT with unmodified acoustic treatment absorption coefficients.**

## 5. DIFFUSION AND REVERBERATION

A diffuse sound field is described by Cox and D'Antonio to have uniform reflected energy density throughout the room and where all directions of sound propagation are equally probable [5]. Extensive research has been done by Cox and D'Antonio and others exploring the effects of diffusion on reverberation. In an online paper [8], Dalenbäck states that by redirecting the reflected sound in many directions, diffuse reflection allows room surfaces to be hit by sound in a more uniform manner so that absorbing surfaces are better utilized. He also discusses the example of a rectangular, predominantly concrete gymnasium with absorption only on the ceiling where the measured RT at 1 kHz was 5.7 sec compared to the predicted RT at 1 kHz which varied from 1.9 sec to 13 sec using a variety of statistical and geometric computerized prediction methods that did not account for diffuse reflections. With geometric computer prediction models that accounted for surface scattering the predicted RT at 1 kHz were between 5.1 and 5.9 sec.

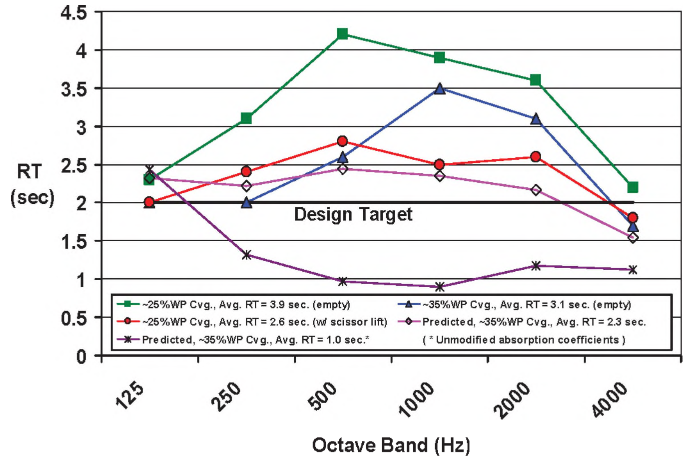


**Figure 4. Comparison of initial, re-measured and predicted RT in Gym B-1. Squares: ~25% wall panel coverage. Circles: ~25% wall panel coverage (with scissor lift present). Triangles: ~35% wall panel coverage. Diamonds: predicted RT with modified acoustic treatment absorption coefficients. Asterisks: predicted RT with unmodified acoustic treatment absorption coefficients.**

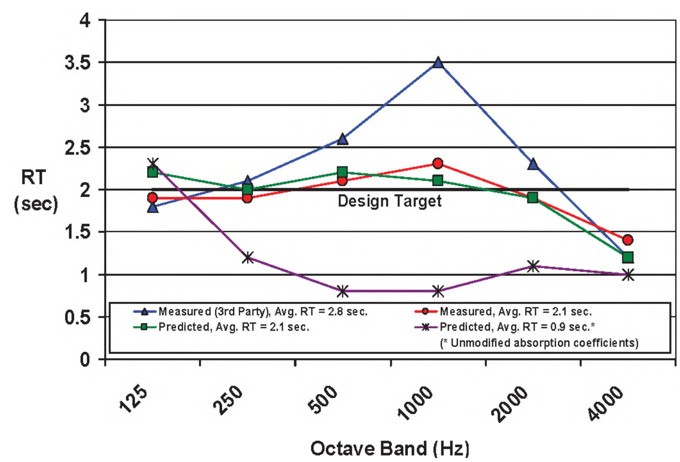


**Figure 5. Comparison of initial, re-measured and predicted RT in Gym B-2 with ~40% wall panel coverage. Triangles: independent 3$^{rd}$ party measurements [7] with the room empty. Circles: initial measurements with construction materials present (see Figures 7, 8 & 9). Squares: predicted RT with modified acoustic treatment absorption coefficients. Asterisks: predicted RT with unmodified acoustic treatment absorption coefficients.**

In their July 2000 paper [9] Bistafa and Bradley give an overview of various RT prediction formulae and their limitations with regards to non-uniform distribution of absorption and refer to the extensive work by Hodgson [10][11] in this field. In their study of RT in an unoccupied simulated classroom they found it necessary to add gypsum board diffuser panels to the room to increase diffuseness and that increasing the number of panels resulted in lower reverberation times.

The requirement for a sufficiently diffuse sound field is established for laboratory measurements in ASTM C423 - 09a [12]. This is typically achieved with fixed and/or rotating sound-reflective panels hung or distributed with random orientations about the volume of the reverberation room to interrupt standing wave modes. ASTM C423 states that it has been found that in rectangular rooms the area (both sides) of diffusers required to achieve satisfactory diffusion is 15 to 25% of the total surface area of the room.

In this study all of the gymnasia except for the two following cases were measured completely empty (neglecting the measurement equipment and operator): As mentioned previously, for one measurement session in Gym B-1, a scissor lift was located at one end of the room and a 1.2 m by 2.4 m Tectum board was leaning against a wall (see Figure 6). During a measurement session in Gym B-2, a few boxes of construction materials were present on the floor (see Figures 7, 8 & 9).

**Figure 6. Scissor lift and Tectum panel in Gym B-1.**

In both cases, these objects were judged at the time not to be large enough in area or volume to make a significant difference in the RT. However, the diffusion that they may have provided was not considered. In both cases lower RT were measured with the most dramatic difference in the later case: a mid-frequency average RT of 2.1 seconds, reasonably close to the ODEON predictions and significantly lower than measurements in the same room conducted roughly one week later by an independent 3rd party with the room empty (see Figure 5).

The third band of wall panels appeared to be having some effect in the Type B gymnasia measured with the additional objects but not in the other (empty) gyms. Further investigation finally lead to the hypothesis of an insufficiently diffuse sound field and uninterrupted standing wave modes in the lower untreated portion of the room contributing to the unexpected results. It was suggested that providing some diffusive objects to break up these reflections might provide results closer to a minimally occupied condition and to the predictions. This hypothesis was tested and the RT re-measured in Gym B-1 with some plywood panels and also with a few people.

**Figure 7. Construction materials in Gym B-2 (view 1).**

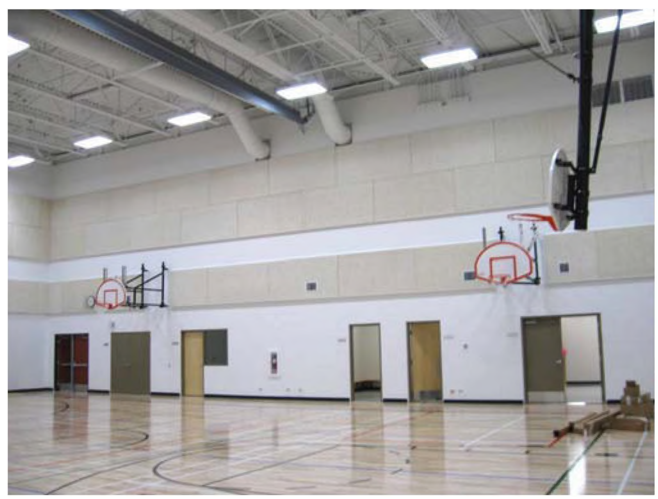

**Figure 8. Construction materials in Gym B-2 (view 2).**

Five different conditions were measured; an empty gym, addition of people, and three levels of diffusion. Diffusion was varied with plywood sheets, 1.2 m x 2.4 m x 12.7 mm thick, stood on end at various locations throughout the gym. Ten of these plywood sheets were fastened together at one end to form five self-supporting A-frame units. The remaining five plywood sheets were leaned against the volleyball net and supporting end poles at the mid point of the gym (see Figure 10). Sheets were removed and the measurements repeated. The measurements were also repeated with the room empty and again with the equipment operator plus four other adults.

**Figure 9. Construction materials in Gym B-2 (view 3).**

**Figure 10. Plywood sheets in Gym B-1**

## 6. RESULTS WITH ADDED DIFFUSION

The results for the re-measured Gym B-1 with approximately 35% wall panel coverage and with and without the plywood panels (totalling between 2% and 5% of the room surface area) to increase sound diffusion in the room are presented in Figure 11. All plotted measurements were conducted with the room empty except for the noted fittings or occupants plus the measurement equipment and operator. For the RT measurements with plywood sheets two stepladders were also present. The predicted RT are for the empty room (i.e. no people or plywood panels).

The addition of as few as four people or five plywood sheets was found to significantly reduce the measured RT, closer to the modeled predictions, with between a 0.6 sec and 1 sec reduction observed in the mid-band average RT from the empty condition. This decrease in the measured reverberation times is more than can be accounted for by the sound absorption provided by four additional adult bodies alone.

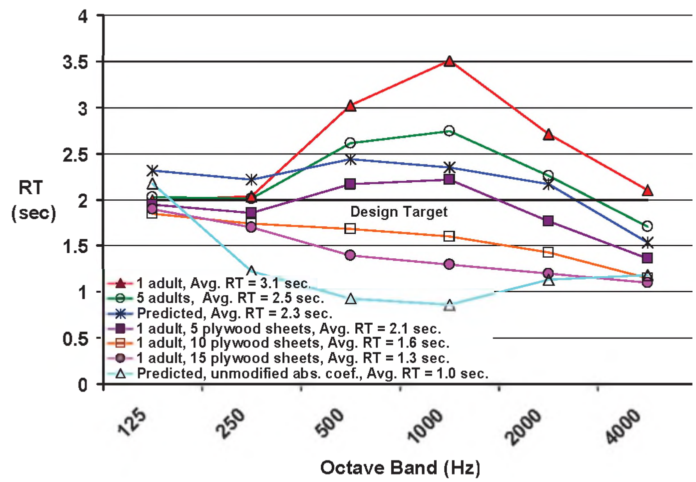


**Figure 11. Comparison of measured and predicted RT in Gym B-1 with ~35% wall panel coverage showing the effect of the addition of people and plywood sheets. Triangles: room empty (except for 1 adult). Open circles: 5 adults. Asterisks: predicted RT with modified acoustic treatment absorption coefficients. Solid squares: 1 adult, 5 plywood sheets. Open squares: 1 adult, 10 plywood sheets. Solid circles: 1 adult, 15 plywood sheets. Open triangles: predicted RT with unmodified acoustic treatment absorption coefficients.**

The low frequency RT did not appear to be particularly sensitive to the addition of the plywood however the times in the 500 to 4000 Hz bands were significantly reduced. With the addition of the plywood panels, between a 1.3 sec and 2.2 sec reduction in the RT at 1000 Hz from the empty condition was observed resulting in a mid-band average RT of between 1.3 sec and 2.1 sec compared to 3.1 sec for the empty room.

Similar measurements were repeated by Alberta Infrastructure in Gym A-2 and Gym B-2. Their findings (not yet published) were similar with regards to the effect of diffusive elements on the measured RT (see Figure 12).

During their measurements the importance of plywood placement was not extensively evaluated, however some variations were deliberately introduced to help evaluate any effect this may have. Generally it appeared that the RT were not particularly sensitive to the location of the plywood.

They also reported that the physical variations between the two types of gymnasia did not result in any major differences in RT. Eight (8) and 18 adults were also randomly distributed throughout the gymnasia while reverberation testing took place. Using body surface areas calculated with the DuBois formula as suggested by ASHRAE and height and weight determined using Standard Pediatric Data from the National Centre for Health Statistics, they deduced that the equivalent of 15 (K-6) students (9 year old males) results in the same reverberant characteristics as approximately four sheets of plywood and that increasing the number of student equivalents to 34, lowers the reverberation to the same degree as approximately ten sheets of plywood.

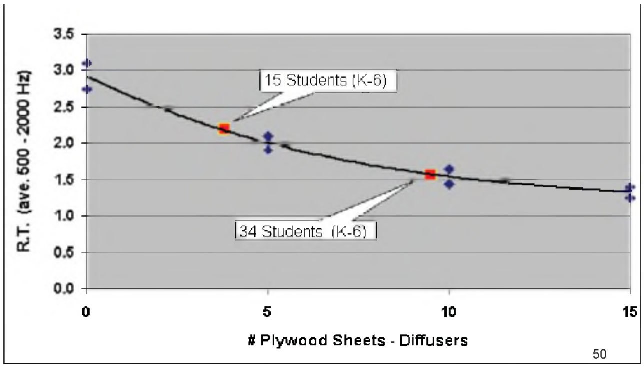


**Figure 12. Alberta Infrastructure measured RT in Gym A-2 (upper diamonds) and Gym B-2 (lower diamonds) with ~40% wall panel coverage.**

As a result of these measurements Alberta Infrastructure decided that to more fairly and accurately assess the RT criterion applicable to the project, it was important to add diffusion in an appropriate amount to emulate the diffusion that would be provided by a typical class size of 25 (K-6) students and one teacher.

They prescribed that this could be accomplished by adding seven, 1.2 m x 2.4 m sheets of 16 mm to 19 mm thick plywood distributed throughout the gym as described above.

## 7. ADDITIONAL COMMENTS

It could be argued that plywood sheets are not ‘diffusers’ per say as they are generally flat and smooth and reflections from them would be predominantly specular. Sound reflectors or re-directors may be a more accurate description of these panels although they were found to increase the level of diffusion or sound mixing in the room.

It has been suggested that the plywood panels change the propagation and reflection of the sound waves in the lower portion of the room and thus of the reflected sound incident on the acoustically absorptive wall panels and acoustic deck, resulting in more effective absorption by the acoustic treatments.

RT measurements in the upper (treated) portion of the room were not conducted during this study but may have yielded some interesting results. One possible explanation for the increase in measured mid-band average RT in the empty rooms with the addition of additional absorptive wall panels could be that by adding absorption in the upper portion of the room while leaving the lower portion of the room (where the measurements were conducted) acoustically reflective actually made the sound field in the room less diffuse. This hypothesis requires further study.


## ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of Bird-Graham Schools A Joint Venture, the guidance and information provided by David Quirt (IRC-NRC), John Bradley (IRC-NRC), Murray Hodgson (UBC), Michel Morin (MJM), Kelly Kruger (AI), Jim Weir (B&K), and the acoustical modelling assistance provided by Matthew Faszer (FFA) and Carl Grant (FFA).


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# NONLINEAR ACOUSTIC PROPERTIES OF PERFORATED LINERS: NEW THEORY AND EXPERIMENT

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## 1. INTRODUCTION

Drastic noise reduction from modern high-bypass turbofan engines using acoustic liners is an important part of developing a novel environmentally- friendly aircraft engine technology. However, the development of new concepts for effective noise suppression needs more study. In fact, a number of techniques for determining the acoustic impedance of these liners have been developed over the last five decades. In addition, a number of models have been developed to predict the acoustic impedance of locally reacting liners [1-10].

However, the existing models still have some limitations to quantify the effects that are potential contributors to nonlinear impedance at high frequencies. In addition, they need more rigorous investigation in further understanding of diverse physical phenomena involved in the propagation through holes. These phenomena are becoming increasingly complex task because of the nonlinear assumptions due to high sound pressure levels (SPL) or liner material nonlinearities.

In order to circumvent these disadvantages, a new nonlinear impedance model of a micro-perforated panel (MPP) has been developed using an equivalent fluid [2] concept. This model is relatively easy to integrate into the Transfer Matrix Method (TMM) to predict performance of multiple MPP sound absorbers.

## 2. THEORY

There are a number of classical linear models for micro-perforated plates. Atalla and Sgard [2] give a review and show that a perforated plate or screen can be modeled as an equivalent fluid following the Johnson- Champoux-Allard approach [1] with an equivalent tortuosity:

$$Z_{perf-linear} = j\frac{\omega\tilde{\rho}_e\, t}{\phi} \tag{1}$$

In this equation $\phi$ is the percentage of open area (porosity), $t$ the plate's thickness and $\tilde{\rho}_e$ the effective density. The latter is linked to the air density $\rho_0$ and dynamic tortuosity $\tilde{\alpha}$, where $\tilde{\rho}_e = \rho_0\tilde{\alpha}$ with $\alpha_\infty$ denotes the geometrical tortuosity. To take into account the effects of mass on the pores, the following correction for the tortuosity is used $\alpha_\infty(\omega) = 1 + 2\varepsilon_e/t$. Here $r$ represents the radius of the perforations and $\varepsilon_e$ a correction length approximated by: $\varepsilon_e = 0.48\sqrt{\pi r^2}$. The end-correction is based on the low frequency limit of the radiation impedance of a piston in a rigid baffle. This can be implemented assuming that the velocity in the hole is uniform. However, this assumption is not valid at high SPL since this end correction doesn't predict the experimentally observed decrease in the mass reactance with increasing sound intensity. This is perhaps due to the fact that the piston radiation at the ends of the narrow tube is partly blown by the jet formed at high SPL. The classical model involves the effect of the array of holes, especially on the end correction of the hole impedance which needs further investigation. The main goal of this study was to extend the classical model to build a reliable nonlinear model to better describe the nonlinear effects. Therefore it is proposed to change the linear-end correction of the acoustic mass in terms of tortuosity [8, 9]. For this purpose, several schemes have been developed leading to:

$$\alpha_\infty = 1 + \varepsilon_{NL} \times \psi\left(\sqrt{\phi}\right) \times \delta_{im} \times \frac{2\varepsilon_e}{t} \tag{2}$$

The proposed nonlinear equivalent tortuosity is given by the following nonlinear end correction. The first term in equation 2 corrects for the non-linear effect on the correction length:

$$\varepsilon_{NL} = \frac{1}{1 + V_{ac}/\phi c_0} \tag{3}$$

The second term in equation 2 accounts for the effect of adjacent holes on the end correction (Interaction effects) by the Fok function:

$$\psi\left(\sqrt{\phi}\right) = \left[\sum_{n=0}^{8} a_n \left(\sqrt{\phi}\right)^n\right]^{-1} \tag{4}$$

Its effect is to decrease the end correction with increasing porosity. The nonlinear reactance end correction to account for sound amplitude effects. This is a fit to experimental data, was introduced by Elnady [10]: $\delta_{im} = 0.5$. In addition, these corrections take into account the effect of vibration of air molecules vibrating tube in the viscous boundary layer [7, 8]. The effect of the vibration of the air particles on the baffle in the vicinity of the aperture increases the thermo-viscous frictions. To take this effect into account, Ingard and Labate [7] proposed an additional factor on the resistive part of the hole impedance. Denoting by $R_s$ the surface resistance, the second resistive part of the viscous loss effect is:

$$\theta_{viscous} = \frac{4R_s}{\phi\rho_0 c}\frac{t}{d} = \frac{\sqrt{8\nu\omega}}{\phi c}\frac{t}{d}, \text{ with } R_s = \frac{1}{2}\sqrt{2\eta\omega\rho_0} \tag{5}$$

Finally, to account for the effect of high SPL on the flow resistance of the system, including the perforation shape effect, the model of Melling [5] is used to correct the flow resistance of the system:

$$R_{NL} = R_{Melling} = \frac{\left(1-\phi^2\right)}{2c\left(\phi C_D\right)^2} V_{ac} \qquad (6)$$

In this equation $V_{ac}$ denotes the flow velocity inside the hole and $C_D$ the perforation discharge coefficient. In consequence, the proposed impedance model takes the form:

$$Z_{perf-Nonlinear} = R_{NL} + \left( \frac{\sqrt{8\upsilon\omega t}}{cd} + j\omega\tilde{\tilde{\rho}}_e t \right) \Big/ \phi C_D \, , \qquad (7)$$

with $\tilde{\tilde{\rho}}_e = \rho_0 \tilde{\alpha}_\infty \left( 1 + \frac{\sigma\phi}{j\omega\rho_0\tilde{\alpha}_\infty} G_j(\omega) \right)$ (8)

## 3. EXPERIMENTAL VALIDATION

The measurements are made using in-house developed nonlinear impedance tube. The tube measurements are based on the classical two-microphone transfer function test method as described in ASTM E1050-98. In-house software was developed in Labview and Matlab to control the measurements and process the data. Reference velocity and pressure were calculated at the surface of the sample by transfer function method. As a first validation of the model, an experimental investigation of the linear and nonlinear impedance of single degree of freedom 1DOF and 2DOF MMP based liners are used with different type of geometric parameter. An equivalent fluid model for MPP was developed and implemented within the TMM methodology. For the experimental investigation, 1mm thick and 1mm diameter aluminum perforated plate samples were tested with different open areas from 4 to 15%. The test sample is a perforated plate backed by a 25mm air cavity. Fifteen perforate samples were tested in all. The impedance tests were performed using pure tones excitations at three SPLs (110, 130 and 150 dB) in the 500 Hz to 6500 Hz frequency range. Figure 1 and 2 show examples of the comparison between test and predictions for the resistance and reactance part at 150 dB SPL. The measured impedance are presented (red curve) and compared to theoretical models (blue curve). This shows that the tests are repeatable.

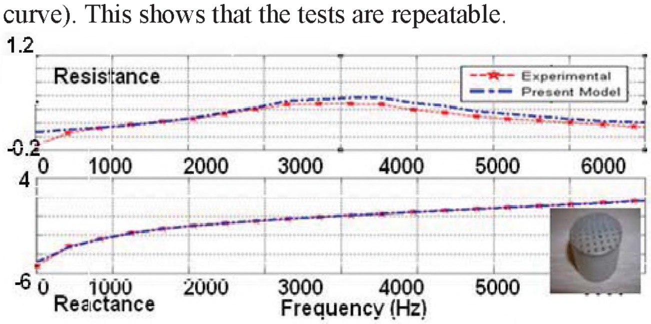


**Figure1. Model vs. test: SDOF m with Pure tone 150 dB OASPL MPP A (POA =13.95%) - cavity 25mm**

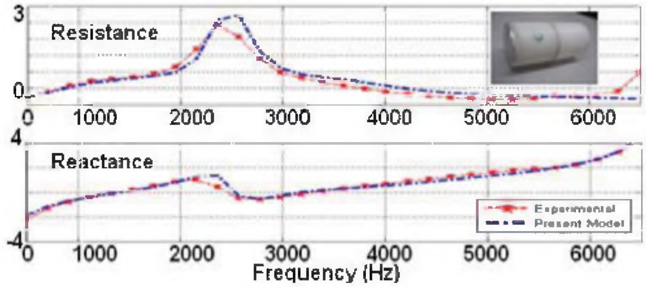


**Figure2. Model vs. test: DDOF with Pure tone 150 dB OASPL MPPA (POA =13.95%) – top cavity 25mm - MPP B (POA =7.37%) – bottom cavity 25mm**

We can see that there is a good agreement between the model and the experiments for the reactance part. This confirms the correction of the radiation part of the present model. Also, the new model has better prediction in linear and nonlinear regimes.

## 4. CONCLUSIONS

A fluid equivalent based model for MPP is presented and implemented within the TMM. It was validated in both linear and non-linear regimes using a set of 5 MPPS with various parameters in both SDOF and DDOF configurations. Excellent agreement has been found for the majority of tested configurations. However, more testing and complex configurations, such us combination with Honeycombs with embedded mesh caps, are necessary before the practical use of the model for design purposes.

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## ACKNOWLEDGEMENTS

This work was supported by Pratt & Whitney Canada (PWC) and the Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ).

# OBITUARY / OBITUAIRE - PAIGE, THOMAS STEPHEN (MSC, PENG)

With his family by his side, Tom peacefully, but unexpectedly, passed away on Friday, September 30, 2011 at Trillium Health Care (Mississauga Site) in his 64th year.

Beloved husband to Bernice. Father to Christy McAllister (David), Heidi Dempster (David) and Clayton (Natalie Fusco). Gigi to Brittany "Paige", Lexa, Madison and Cole. Brother to Mimi Paige (Lothar Bahr). Tom was born in Winnipeg, Manitoba to Joanna (Okolita) and Stephen Paige.

Tom's childhood was not easy having suffered severely from rheumatic fevers, which also left him deaf for several years, although later surgery partially corrected this. Tom said that this period of deafness profoundly affected his life, and perhaps it was fate that later drew him into noise control, where he could benefit people by helping to prevent hearing loss.

Tom received a Masters Degree in Acoustical Engineering at the University of Manitoba and then worked there for many years. The Paige family then moved to Mississauga in 1988 so Tom could work on the large CBC project in Toronto for Vibron Ltd., now known as Kinetics Noise Control.

Tom had worked in representing Kinetics internationally on many important industry committees, which helped shape many of the standards that we use today, as living proof of his legacy and significant contribution. Tom's unassuming style, honesty and innate genius was respected and appreciated by the many people he interacted with over the course of these many years. Tom served at Kinetics as the senior applications engineer for some 22 years, and just celebrated his retirement in December 2010.

The Funeral Service was conducted on Monday, October 3rd with a Memorial Service in Winnipeg planned for at a later date.

Tom loved his Bernice and his family of children and grandchildren, and enjoyed spending time with them. He kept in touch with us and his passing instils a profound sense of loss in all of us. Tom's work made a difference in the world. May we honor his memory in striving to keep high standards of integrity and ethics, and by each of us trying, in our own ways, to make the world a better place for others to live in.

A tribute by Ruchard Anthony and Mehrzad Salkhordeh

Kinetics Noise Control, Missisauga, Ontario

## Canada Wide Science Fair

### From File Reports

Emily Been and Joshua Thon from Calgary won this year's science fair award for their work on "The Fractal Geometry of Blood Clots."

Emily Been is a senior in the French immersion program at William Aberhart High School in Calgary, Alberta. Several of her interests include piano, choir, dance and volunteering at horseback riding. She is on the school cross country running team, participates in leadership events and organizes blood donation drives through the school. After high school Emily plans to study engineering in the research domain.

Joshua Thon is a grade twelve student from Calgary, Alberta. A self-described debate fiend, he enjoys participating in debates as well as teaching younger students how to debate. Joshua also enjoys playing the trumpet, which he plays in three school ensembles, whose focus ranges from jazz to classical music. He also takes great pleasure in informing himself on matters of world politics and science. After his graduation in June, Joshua plans to study engineering with an eventual specialization in biomedical engineering.

The full article is reproduced below.

# The Fractal Geometry of Blood Clots*

**Joshua Thon, Elizabeth Keys, Hannah Park and Emily Been**

William Aberhart High School and University of Calgary, Health Sciences, Calgary, Alberta, Canada

**Editor's Note:** The submission by Been and Thon was reformatted and edited to fit in to the Journal format.

## 1 ABSTRACT

We describe a simple method to characterize the fractal dimension of blood coagulation using high-resolution vital light microscopy. We also report that the fractal dimension is a dynamic process that can be influenced by external acoustic vibrations.

## 2 BACKGROUND INFORMATION

Fractal geometry is a scientific method for measuring, analyzing and categorizing physiological structures. The term fractal refers to a structure that exhibits self-similarity at a range of magnifications. Fractal dimension is a common measurement used to determine the complexity of a fractal shape, which is also how completely the shape fills the plane of view. The software we used, Benoit, uses the box-counting method to determine the fractal dimension. It uses a rotating grid to graph the number of boxes filled to box side length on an exponentially scaled graph. The slope of this graphed line is the fractal dimension.

Presently there are two main ways to assess blood clotting; bleeding time and viscoelasticity. Both are relatively insensitive. The bleeding time provides general information on both the integrity of the blood vessels as well as the coagulation pathways. Measuring viscoelasticity is a highly complicated procedure involving expensive equipment. [1]

Cymatics is the study of the effects of sound on physical substances. It has been shown to change the physical structure of crystals [2] and has several applications in medical practice. In the latter role it is used in diagnostics such as ultrasound imaging as well as therapeutically to fragment renal and gall bladder stones [3].

The proposed model of our experiment was to collect blood, apply a pure frequency as the blood clot develops, and then view and record clotting with a Richardson Light Microscope. We hypothesized that frequency would affect the complexity of the clot. We also examined the evolution of the complexity of the clot as it formed.

## 3 METHODS/EXPERIMENTS

Blood samples were imaged on a Richardson RTM-3 microscope equipped with a Sony 3CCD Exwave HAD camera [4]. The microscope is used to image living structures in their natural state and has high resolution (~100 nanometers) and suitable for imaging structures such as fibrin crystals. The subjects fasted overnight and were well hydrated. A finger was pricked with a BD GenieTM Lancet. The droplet of blood was transferred directly to a glass slide. Clotting was recorded by video microscopy, an example of which can be viewed online [5]. For the sound studies, control droplets were allowed to coagulate in the absence of sound. Other droplets were exposed to one of two different frequencies (170HZ and 14,846HZ). The sound frequencies were delivered through

Protek B-801 8 ohm speakers, directly mounted onto the stage of the microscope.

Photos were taken of areas of plasma between any sizable gap between red blood cells. (Fig. 1) Videos were used for dynamic fractal testing.

The images were edited using image J software and a custom made macro. To avoid bias all images were processed identically. These images were analysed with Benoit fractal analysis software, using the box counting method.
We then compiled the data into spreadsheets for statistical analysis. Comparison between the FD for different frequencies of sound were analyzed using ANOVA. A p value of $<0.05$ was considered to be significant.

## 4 RESULTS

The clots formed from elongate crystals of fibrin, best seen in the areas of plasma/serum between the red blood cells. (Fig 1). The crystals formed a complex mesh with fractal properties. The individual fibres of fibrin were approximately 70 nanometers in diameter at the midpoint. There appeared to be considerable individual variation in the thickness of the fibres as reported by others [6].

In control tests the fractal dimension was dynamic, increasing over 72.7 seconds before reaching a stable state (Fig. 2). The fractal dimension of the fibrin clot in the stable state was relatively constant for this individual. High frequency sound was associated with a higher fractal dimension compared to a low frequency sound (P=0.04) (Fig. 3), indicating that sound could induce changes in the complexity of the fibrin mesh.

## 5 DISCUSSION

This study used FD analysis to determine changes in the structure of a blood clot induced by sound. Dynamic analysis of blood clotting showed increasing FD over time with an S shaped curve. The presence of sound had a statistically significant effect on the formation of the fibrin mesh. An increase in FD corresponded to a higher frequency of sound. FD is likely to be influenced by fibrin strand width, amount of crossing of the crystals and amount of fibrin present. The FD may be useful for diagnosing clotting disorders, identifying risk for thrombosis and for monitoring the effects of pharmaceuticals that affect blood clotting.

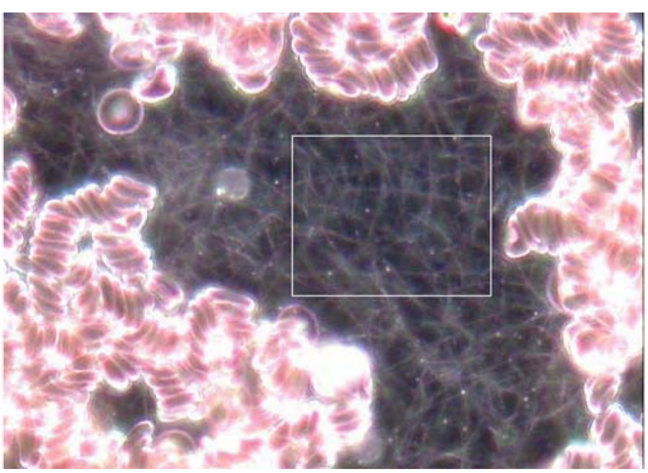

**Figure 1. An example of an image used in the study. The inset box indicates how the images were cropped to sample only the fibrin mesh**

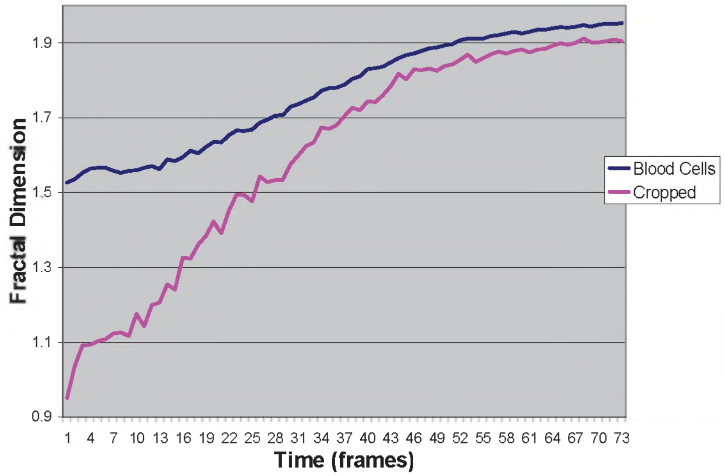


**Fig. 2. Time lapse images were taken every second during the blood clotting process. Both the full image (that included blood cells) and a cropped image (see figure 1) of only fibrin were analyzed and their FDs plotted against time**

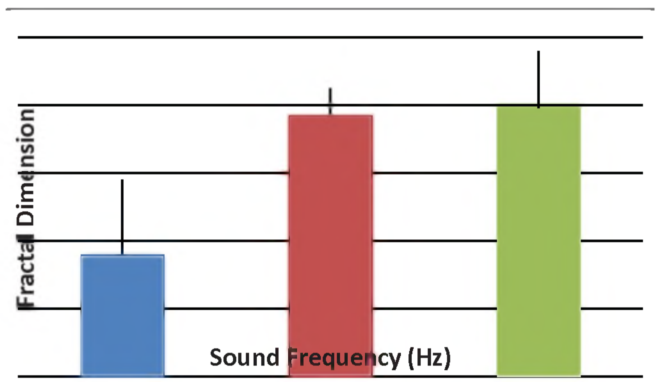


**Fig 3. Blood was subjected to two frequencies of sound during the clotting process. Both frequencies increased the FD but only the highest frequency was statistically significant (P=0.04).**

Arguably the fibrin mesh is not a perfect fractal structure however the mesh is too irregular to be described with Euclidean geometry and exhibits self-similarity on a range of scales.

The theory we propose for why the sound affects the fibrin mesh is based on the nucleation of crystals [7]. Crystals start at random nucleation points when the particles of solute concentrate enough to start a crystal. When a vibration is present the likelihood of interactions between molecules should increase, creating multiple nucleation points and increasing the FD. We would also expect smaller crystals. In this study we did not measure the crystal length.

The fact that the box counting method was successful in measuring small changes in the blood clot is important. The box counting method is sensitive enough to measure minute changes in the blood clot caused by sound. These changes are not detectable with the naked eye. Because of this newfound possibility to observe exact and detailed changes in the complexity, it opens the door to a completely new type of diagnostic testing.

In summary we have shown that a blood clot has fractal properties and that sound vibrations affect it significantly. We have also shown that using the box counting method to determine fractal dimension is an accurate and effective way to measure changes in the complexity of blood clots. Compared to other methods of measuring clotting, the fractal analysis is relatively non-intrusive and could be developed into a rapid and sensitive test of complexity of the fibrin mesh. It thus has potential to be deployed in the clinical setting.

## ACKNOWLEDGEMENTS

The authors of this paper wish to thank David Evan Nelson for statistical assistance. We would also like to thank Dr. Francis Green and Dr. Mauro Tambasco for supervision of the project and consultation in the fields of pathology and fractal geometry respectively.

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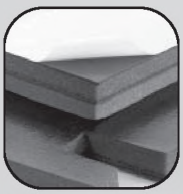





Blachford

## Canadian Acoustical Association

### Minutes of the Board of Directors Meeting

Québec City, Québec
11 October 2011

Present: Christian Giguère (chair), Jérémie Voix, Hugues Nélisse, Tim Kelsall, Clair Wakefield, Stan Dosso, Rich Peppin, Ramani Ramakrishnan, Dalila Giusti, Bradford Gover, Roberto Racca

Participating by Teleconference: Frank Russo

Regrets: Sean Pecknold

The meeting was called to order at 6:05 p.m. Minutes of previous Board of Directors meeting on 07 May 2011 were approved as published in June 2011 issue of *Canadian Acoustics*. *(Moved by R. Peppin, seconded R. Ramakrishnan, carried)*.

### President's Report

Christian Giguère reported that there have been no major problems in the affairs of the Association. In addition to the successful planning of CAA annual conferences, the CAA has been liaising with other organizations regarding participation in or co-sponsorship of their meetings. These are important activities in maintaining and increasing the visibility and relevance of the CAA. The most pressing issue remains the need to transition to online membership and database management capabilities. Christian also reminded the Board that he would not seek re-election as President of the CAA next year, in Oct 2012.

### Secretary's Report

Bradford Gover reported that routine processes of the Association are proceeding normally, despite the delays associated with implementing the online membership system.

With respect to routine CAA communications:

- Annual filing with Corporations Canada was submitted and acknowledged.
- Invoices from I-INCE and ICA were received and our Treasurer handled payment.

Secretarial operating costs for the fiscal year totaled $437.15, for Corporations Canada fees, and postal box rentals. A budget of $1000 is proposed for next fiscal year, in anticipation of higher mailing costs (for invoices and receipts).

Paid new memberships and renewals are down this year from typical numbers. Two years ago, in Sept 2009, there were 374 paid renewals. This year, in Sept 2011, there are 232. There are a large number of members who were in good standing in 2010, and were sent the invoice for 2011, but have not yet paid (labeled "Outstanding 2011" in the table below).

| Category | Paid 2011 | Change From 2009 | Outstanding 2011 |
|---|---|---|---|
| Member | 148 | –97 | 113 |
| Emeritus | 2 | +1 | 0 |
| Student | 33 | –27 | 31 |
| Subscriber | 49 | –19 | 26 |
| | **232** | **–142** | **170** |

The drop in renewals is largely due to the delays in setting up the online membership system. In anticipation of the online system being available, members were instructed with their 2010 invoices that the preferred method of payment was 'online', and this option is still not available. Furthermore, in 2011, invoices were for the first time sent electronically (by email), and the response rate has not been as high as expected. Following discussion, the decision was made to contact outstanding members and revert to paper mailings for next year. *(Approval of report moved by R. Racca, seconded T. Kelsall, carried)*

## Treasurer's Report

The Treasurer, Dalila Giusti, submitted a report including a preliminary financial statement for the fiscal year. Most expenses were essentially as budgeted, although journal costs were lower than forecasted, and not all Student Travel Award money was paid out. Revenue from membership dues was down (due to the large number of pending renewals), however, revenue from journal advertising was up. The 2010 Conference (Victoria) made a profit of $19,000, so overall, revenue well exceeded expenses, and exceeded costs for student awards.

The proposed budget for 2011-2012 was also discussed. At present, the planned budget for 2012 predicts near balance. No request was made to increase membership rates.

The Treasurer's report was accepted. *(Moved S. Dosso, seconded R. Ramakrishnan, carried)*

## Editor's Report

The Editor, Ramani Ramakrishnan, gave a brief report on issues related to *Canadian Acoustics*. Highlights included:

- All issues have been published on schedule.
- Preparations for eventual online publication of the journal have once again progressed modestly.
- Plans for journal issues in 2012 include:
  - March: Special issue on Underwater Acoustics.
  - June: Special French language issue.
  - September: Proceedings of the annual CAA Conference.

Ramani once again reminded the Board that, as announced in the minutes of the spring BoD meeting printed in the June 2010 issue, he is planning to not seek election as Editor in Chief in 2013, and would like to use the time until then to assist in the transition of a replacement. Any individuals interested in being considered as the next editor are asked to contact Ramani as soon as possible.

## CAA Conferences – Past, Present & Future

*2010 (Victoria):* A final report for the conference has been received from conference chair Stan Dosso, with the final transfer of funds. The Board thanked the organizers for the high quality of the very successful meeting.

*2011 (Québec City):* The conference at the Hôtel Château Laurier Québec, October 12-14, has 115 papers scheduled and 13 exhibitors. Christian Giguère is Chair, Jérémie Voix and Hugues Nélisse are Technical Co-Chairs, and André L'Espérance organized the exhibition.

*2012 (Banff):* The conference will be held in mid-October in Banff. Conference Chair Stan Dosso has reassembled the successful team from Victoria, with Roberto Racca as Technical Chair, and Clair Wakefield organizing the exhibition. Watch for announcements in *Canadian Acoustics,* and on the website.

Subsequent meetings: Several options for future CAA conferences were discussed. At present, there are no firm plans for 2013 or later. One possibility for 2013 is to not hold a CAA conference, but rather to integrate into the International Congress on Acoustics (ICA) to be held in Montréal in June. Also, the CAA will sponsor a satellite International Symposium on Room Acoustics (ISRA) to be held in Toronto, in coordination with the ICA.

## Awards

Frank Russo presented a report summarizing decisions by the coordinators for all CAA awards. There were eligible applications for all awards except the Hetu Prize, and winners have been selected. Winners were announced on 13 October at the banquet, and in this issue of *Canadian Acoustics*.

There was discussion of the two new student awards that were approved by the Board in Oct 2010: one in the field of "Architectural Acoustics", and one in the field of "Psychological Acoustics", and of the monetary structure of the awards in general. It was proposed to reduce the value of the Bell Student Prize in Speech Communication and Hearing from $800 to $500, to reduce the value of the two Directors' Awards from $500 each to $250 each, and to set the value of the two new awards at $500 each. *(Moved F. Russo, second R. Ramakrishnan, carried)*

The Student Travel Awards were also discussed. Given the difficulty in administering them, it was suggested that they are not effectively serving the purpose of encouraging and rewarding student participation at the Conferences. Frank Russo agreed to draft new procedures for awarding the funds, and to distribute to the Board for consideration.

A discussion followed about how to best adjudicate the suitability of applicants for student awards. It was suggested to require, for all graduate level awards, a CV and a letter of support from the applicant's supervisor. *(Moved S. Dosso, second F. Russo, carried)*

### Acoustical Standards Committee

Tim Kelsall reported on the status of the CAA Acoustical Standards Committee. This committee was formed last year after the Canadian Standards Association (CSA) disbanded committee Z107, and reorganized their remaining standards related to acoustics. The CAA Acoustical Standards Committee met concurrently with the new CSA standards committee on 12 October. A report is printed in this issue.

### CAA Website

Christian Giguère reported on behalf of Sean Pecknold that routine maintenance of and updates to the website have been ongoing. A major revision is still on hold until such time as the new online member database and registration capabilities come online.

### Other Business

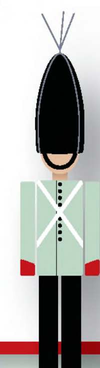
There were several items of other business:

- Clair Wakefield reported an inquiry from I-INCE regarding Canadian input to an activity tracking research on transportation noise. It was discussed, and suggested that the CAA Environmental Standards Subcommittee follow up. Tim Kelsall volunteered to investigate.
- Following on previous Board of Directors discussions of a new logo for the Association, Christian Giguère reported that he will get back to the designer with feedback.
- Stan Dosso led a brief discussion of nominations for the election at the Annual General Meeting (See AGM minutes for details).

### Adjournment

Meeting adjourned at 9:45 p.m. *(Moved J. Voix, seconded R. Ramakrishnan, carried)*





## Canadian Acoustical Association

### Minutes of Annual General Meeting

Québec City, Québec
13 October 2011

### Call to Order

President Christian Giguère called the meeting to order at 5:32 p.m. with 31 members present, and presented the Agenda for acceptance *(Moved S. Dosso, second R. Peppin, carried.)*

Minutes of the previous Annual General Meeting on 14 October 2010 in Victoria were approved as printed in the December 2010 issue of *Canadian Acoustics*. *(Moved R. Peppin, second A. Behar, carried.)*

### President's Report

Christian Giguère briefly summarized his report to the Board meeting on 11 October. He emphasized that the society is in good shape financially, has had a series of successful annual Conferences – 70 new members have joined at this Conference – and is running smoothly with respect to the journal and the awards. He thanked all those who have made contributions to our activities. He also reported that the key priority for the coming year is shifting our operations to a new web-based system to facilitate routine membership and financial transactions.

### Secretary's Report

Bradford Gover gave an overview of membership and operational activity.

- The total of 232 paid renewals and new memberships is down from last year, presumably due to the instructions to members to wait for online payment, and also lower than expected response rate to the 2011 Invoices that were sent by email. Those members whose payment is pending will be contacted.
- An itemized account of the administrative budget of $437 was presented to the Board.
- Steps are ongoing towards shifting the membership database and renewal process to an online system, and promoting a shift towards more email and online transactions, to handle routine processes with less volunteer effort.

*(Acceptance of Secretary's report moved by R. Ramakrishnan, second P. VanDelden, carried.)*

### Treasurer's Report

Dalila Giusti presented an overview of her written report to the Board on CAA finances. CAA is in good financial shape, with total assets of $311,615 at fiscal year-end (before audit). Total assets rose from last year, and some investments were redistributed to manage the interest revenue stream.

In 2012, a near-balanced budget is predicted. The Board is recommending leaving the membership dues for 2011 unchanged.
*(Acceptance of Treasurer's report moved by T. Kelsall, second R. Racca, carried.)*

### Editor's Report

Ramani Ramakrishnan gave the Editor's report. *Canadian Acoustics* production has proceeded smoothly throughout the year, and content for issues is largely set through September 2012.

Ramani reminded the membership that he does not intend to seek re-election as Editor in Chief after 2012. He would like to work closely with a replacement to assist with the transition. Anyone who might like to seek election to the position of Editor is asked to contact Ramani as soon as possible.

### Award Coordinator's Report

On behalf of Frank Russo, Christian Giguère reported that this year CAA is awarding all prizes with the exception of the Hetu Prize. In addition, we have sponsors for the three student paper awards for presentations at the conference. (For names of award recipients, see the separate announcement in this issue.)

Also, two new prizes have been recently created by the board, one in Architectural Acoustics, and one in Psychological Acoustics. The Board has decided to set the monetary value of these awards at $500 each.

## Past and Future Meetings

Reports were presented on the past, present and future annual meetings:

2010 (Victoria): A final report for the conference has been received from conference chair Stan Dosso, with the final transfer of funds. The organizers were thanked for the high quality of the very successful meeting.

2011 (Québec City): The conference at the Hôtel Château Laurier Québec, October 12-14, has 115 papers scheduled and 13 exhibitors. Christian Giguère is Chair, Jérémie Voix and Hugues Nélisse are Technical Co-Chairs, and André L'Espérance organized the exhibition.

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Subsequent meetings: Several options for future CAA conferences were discussed. At present, there are no firm plans for 2013 or later. One possibility for 2013 is to not hold a CAA conference, but rather to integrate into the International Congress on Acoustics (ICA) to be held in Montréal in June. Also, the CAA will sponsor a satellite International Symposium on Room Acoustics (ISRA) to be held in Toronto, in coordination with the ICA.

## Acoustical Standards Committee

Tim Kelsall reported on the status of the CAA Acoustical Standards Committee. This committee was formed after the Canadian Standards Association (CSA) disbanded committee Z107, and reorganized their remaining standards related to acoustics. The CAA Acoustical Standards Committee met concurrently with the CSA standards committee on 12 October. A report is printed in this issue.

## Website

Christian Giguère reported on behalf of Sean Pecknold that routine maintenance of and updates to the website have been ongoing. A major revision is still on hold until such time as the new online member database and registration capabilities come online.

## Nominations and Election

CAA corporate bylaws require that we elect the Executive and Directors each year. The Past President, Stan Dosso, presented nominations and managed the election process.

For the election process, Stan read the name(s) of the nominees, and then asked if there were other nominees from the floor.

- Seven of the eight current Directors (namely Roberto Racca, Tim Kelsall, Clair Wakefield, Frank Russo, Sean Pecknold, Jérémie Voix, and Hugues Nelisse) were eligible for re-election, and indicated their willingness to stand.
- Rich Peppin had served the maximum term of 6 years and was not eligible for re-election. Stan identified Kathy Fuller as a nominee for the final Director position.
- Three of the four Executive (Christian Giguère for President, Dalila Giusti for Treasurer, Ramani Ramakrishnan for Editor) were eligible for re-election and indicated their willingness to stand.
- Bradford Gover indicated he was not willing to stand re-election as Executive Secretary. Stan identified Chantal Laroche as a nominee for the position.

In each case, there were no other nominations from the floor, so these nominees were declared elected by acclamation. Rich and Brad were thanked for their service.

## Adjournment

Meeting adjourned at 6:51 p.m. *(Moved R. Peppin, seconded D. Giusti,carried)*

**Canadian Acoustical Association**
**Association canadienne d'acoustique**

# 2011 PRIZE WINNERS / RÉCIPIENDAIRES 2011

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SHAW POSTDOCTORAL PRIZE IN ACOUSTICS /
PRIX POSTDOCTORAL SHAW EN ACOUSTIQUE

**Paolo Ammirante (Macquarie University)**
**Jeff Crukley (University of Western Ontario)**

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BELL GRADUATE STUDENT PRIZE IN SPEECH COMMUNICATION AND HEARING /
PRIX ÉTUDIANT BELL EN COMMUNICATION VERBALE ET AUDITION

**Martin Brummund (Ecole de technologie supérieure)**

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FESSENDEN GRADUATE STUDENT PRIZE IN UNDERWATER ACOUSTICS /
PRIX ÉTUDIANT FESSENDEN EN ACOUSTIQUE SOUS-MARINE

**Gavin Steininger (University of Victoria)**

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ECKEL GRADUATE STUDENT PRIZE IN NOISE CONTROL /
PRIX ÉTUDIANT ECKEL EN CONTRÔLE DU BRUIT

**Chris Bibby (University of British Columbia)**

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CANADA-WIDE SCIENCE FAIR AWARD / PRIX EXPO-SCIENCES PANCANADIENNE

**Joshua Thon and Emily Been (William Aberhart High School, Calgary, AB)**

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DIRECTORS' AWARDS / PRIX DES DIRECTEURS

Non-student / Non-étudiant:

**Josée Lagacé, L'Université d'Ottawa**

Student / Étudiant:

**Joana da Rocha, University of Victoria**

---

STUDENT PRESENTATION AWARDS / PRIX POUR COMMUNICATIONS ÉTUDIANTES
NIAGARA-ON-THE-LAKE (ON), OCTOBER 14-16, 2009

**Antoine Lefebvre (McGill University)**
**Sponsored by Scantek**

**Sonal Bhadane (Ryerson University)**
**Sponsored by Kinetics Noise Control**

**Guilhem Viallet (École de technologie supérieure)**
**Sponsored by Jade Acoustics**

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# CONGRATULATIONS / FÉLICITATIONS

# Canadian Acoustical Association
# Association Canadienne d'Acoustique

## *PRIZE ANNOUNCEMENT • ANNONCE DE PRIX*

### *Prize*

Edgar and Millicent Shaw Postdoctoral Prize in Acoustics
Alexander G. Bell Graduate Student Prize in Speech Communication and Hearing
Eckel Graduate Student Prize in Noise Control
Fessenden Graduate Student Prize in Underwater Acoustics
Raymond Hetu Undergraduate Student Prize in Acoustics

### *Prix*

Prix Post-doctoral Edgar et Millicent Shaw en Acoustique
Prix etudiant Alexander G. Bell en Communication orale et audition ($2^{E}$ ou $3^{E}$ cycle)
Prix etudiant Eckel en Controle du bruit ($2^{E}$ ou $3^{E}$ cycle)
Prix etudiant Fessenden en Acoustique sous-marine ($2^{E}$ ou $3^{E}$ cycle)
Prix etudiant Raymond Hetu en Acoustique ($1^{ER}$ cycle)

**Deadline for Applications:**
**April $30^{th}$ 2012**

***Date limite de soumission des demandes:***
***30 Avril 2012***

Consult CAA website for more information
*Consultez le site Internet de l'ACA pour de plus amples renseignements*
(http://www.caa-aca.ca)


Concerto
4-Channel Multi-Function Acoustic Measuring System
All you need in one system:
- 4-channel SLM Class 1
- RT60, EDT, C80, D50 & Ts
- 4-channel Data Logger
- 4-channel Spectrum Analyzer
- Building and Human Vibration
- Monitoring Station with Remote Access
Custom Modules Available
See demo : www.softdb.com/concerto.php
Remote access via
iPhone or PC


I-Track
Automatic Real-Time Sound Mapping
See demo : www.softdb.com/itrack.php
Automotive
Industrial
Laboratory
Architectural
5-Minute Mapping
Freehand Scanning Without Grid

Mount Rundle from Banff townsite.

## First Announcement

# ACOUSTICS WEEK IN CANADA

## Banff, Alberta, 10-12 Oct. 2012

Acoustics Week in Canada 2012, the annual conference of the Canadian Acoustical Association, will be held in the beautiful town of Banff, Alberta, from 10-12 Oct. 2012. This is the premier Canadian symposium in acoustics and vibration, and this year's exceptional Rocky Mountain setting in Banff National Park (a UNESCO World Heritage Site) will make it an event you won't want to miss. The conference will include three days of plenary lectures and technical sessions on all areas of acoustics, an Exhibition of acoustical equipment and services, the Acoustical Standards Committee Meeting, a Welcome Reception, the Conference Banquet and more.

**Venue and Accommodation** – The Conference will be held at the Banff Park Lodge Resort and Conference Centre, which offers state-of-the-art conference facilities in a mountain-lodge ambience. Accommodation is available at both the Banff Park Lodge (www.banffparklodge.com) and at the neighbouring Bow View Lodge (www.bowview.com), both of which boast an exceptional, quiet location on the banks of the glacier-fed Bow River, but just two blocks from the Banff dining/shopping/entertainment district. The Banff Park Lodge is a Canada Select four-star hotel with 200 luxurious guest rooms, each with balcony or patio and mountain views. The Bow View Lodge is a three-star hotel with 60 comfortable rooms. Participants booking rooms before 5 Sept. 2012 will receive the special conference rate of $127/night for the Banff Park Lodge or $108/night for the Bow View Lodge (single or double occupancy, including complimentary wireless internet and many other amenities).

Banff Park Lodge
RESORT HOTEL AND CONFERENCE CENTRE
ALBERTA, CANADA

Staying at these outstanding conference hotels will place you near your colleagues and all conference activities, and will help make the meeting a financial success to the benefit of future CAA activities. Reduced room rates are in effect from 7 to 14 October, so consider extending your visit to Banff for an autumn holiday! Registration details will be available soon at the conference website.

Moraine Lake, Banff National Park.

Main Street, Banff townsite

Banff Park Lodge, exterior and interior.

**Plenary and Technical Sessions** – Three plenary lectures are planned in areas of broad interest and relevance to the acoustics community. Technical sessions are planned covering all areas of acoustics including:

- Acoustic Standards
- Architectural and Building Acoustics
- Bio-Acoustics and Biomedical Acoustics
- Engineering Acoustics
- Musical Acoustics
- Noise and Noise Control
- Physical Acoustics and Ultrasonics
- Psycho- and Physio-Acoustics
- Shock and Vibration
- Signal Processing
- Speech Sciences and Hearing Sciences
- Underwater Acoustics

If you would like to organize a session on a specific topic, please contact the Technical Chair.

**Exhibition and Sponsorship** – The conference will include an Exhibition of acoustical equipment, products and services on Thursday 11 Oct. 2012. If you or your company are interested in participating in the Exhibition or in sponsoring conference coffee breaks, social events and/or sessions, which provide excellent promotional opportunities, please contact the Exhibition Coordinator.

**Students** – Student participation is strongly encouraged. Travel subsidies and reduced registration fees will be available. Student authors are eligible to win industry-sponsored presentation awards.

**Paper Submission** – The abstract deadline is 15 June 2012. Two-page summary papers for publication in the proceedings issue of *Canadian Acoustics* are due 1 August 2012. Details of the submission procedure will be given at the conference website.

**Registration** – Registration information and forms will be available at the conference website. Early registration at a significantly reduced rate is available until 5 Sept. 2012 and is strongly encouraged.

## Organizing Committee

- Conference Chair: Stan Dosso sdosso@uvic.ca
- Technical Chair: Roberto Racca roberto.racca@jasco.com
- Accounting and Registration:
  Clair Wakefield clair@wakefieldacoustics.com
  Lori Robson lori@wakefieldacoustics.com
- Website: Brendan Rideout brendan.rideout@gmail.com
- Logistics: Lisa Cooper lisa.cooper@jasco.com
- Exhibition: Rich Peppin peppinr@verizon.net

Hiking in Banff National Park.

**Conference Website: www.caa-aca.ca**

Mont Rundle vu de Banff.

**PREMIÈRE ANNONCE**

# SEMAINE CANADIENNE D'ACOUSTIQUE

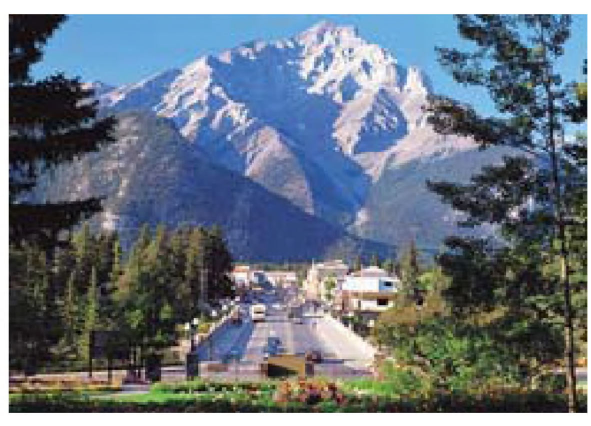
## Banff, Alberta, 10-12 Octobre 2010

La Semaine Canadienne d'Acoustique 2012, la conférence annuelle de l'Association Canadienne d'Acoustique, va prendre place à Banff, AB du 10 au 12 Octobre 2012. C'est le symposium majeur d'acoustique et de vibration au Canada, et cette année, le cadre exceptionnel du Parc National de Banff (site classé Patrimoine Mondial par l'UNESCO), au cœur des Rocheuses, va faire de cette conférence un événement à ne pas manquer. La conférence inclura trois jours de conférences pléniéres, des sessions techniques dans tous les domaines de l'acoustique, une exposition d'équipements et services acoustiques, la réunion du Comité des Standards en Acoustique, une réception de bienvenue, le banquet de la conférence et bien plus encore.

**Centre de conférence et Hébergement** – La conférence prendra place au Banff Park Lodge Resort and Conference Centre, qui offre des installations haut de gamme dans une atmosphère de chalet montagnard. Des logements sont disponibles au Banff Park Lodge (www.banffparklodge.com) ainsi qu'au Bow View Lodge (www.bowview.com), qui sont, tous les deux, des endroits exceptionnels et tranquilles situés sur la rivière Bow et à deux pas du quartier des restaurants/magasins/attractions. Le Banff Park Lodge est un hôtel quatre étoiles *Canada Select* qui offre 200 chambres luxueuses, chacune avec balcon ou patio et vue sur la montagne. Le Bow View Lodge est un hôtel trois étoiles avec 60 chambres confortables. Les participants réservant l'hôtel avant le 5 septembre 2012 recevront un tarif préférentiel de $127/nuit pour le Banff Park Lodge ou $108/nuit pour le Bow View Lodge (occupation simple ou double, incluant la connexion internet sans fil et de nombreux autres avantages). Un séjour dans cet hôtel extraordinaire vous placera au plus prés de vos collègues et de toutes les activités de la conférence, et contribuera à faire de cette réunion un succès financier pour le bénéfice des activités futures de l'ACA. Les chambres à prix réduits sont disponibles du 7 au 14 octobre, donc n'hésitez pas à prolonger votre visite à Banff pour prendre quelques jours de vacances. Les détails d'inscription seront bientôt disponibles sur le site internet de la conférence.

Banff Park Lodge
RESORT HOTEL AND CONFERENCE CENTRE
ALBERTA, CANADA

Lac Moraine, Parc National de Banff.



Main Street, Banff.

Banff Park Lodge, extérieur et intérieur.

**Sessions scientifiques et plénières** – Trois présentations plénières sont prévues dans des domaines d'intérêt général et pertinents pour la communauté d'acoustique. Des sessions techniques seront organisées dans tous les domaines principaux de l'acoustique, incluant les thèmes suivants:

- Standards en acoustique
- Acoustique architecturale et du bâtiment
- Bioacoustique et acoustique biomédicale
- Génie acoustique
- Acoustique Musicale
- Bruit et contrôle du bruit
- Physique acoustique et Ultrasons
- Psycho et Physioacoustique
- Chocs et Vibrations
- Traitement des signaux
- Sciences de la parole et Audition
- Acoustique sous-marine

Si vous désirez proposer et/ou organiser une session spéciale, veuillez contacter le président scientifique.

**Exposition technique et Commandite** – Le congrès inclura une exposition d'équipements, produits et services acoustiques qui prendra place le jeudi 11 Octobre 2012. Si vous ou votre entreprise êtes intéressés à participer à l'exposition ou à commanditer les événements sociaux de la conférence et/ou les sessions, qui offriront d'excellentes opportunités promotionnelles, veuillez contacter le coordinateur de l'exposition.

**Participation étudiante** – La participation étudiante est fortement encouragée. Des subventions de voyages et des frais réduits d'inscription seront disponibles. Les étudiants donnant une présentation sont éligibles pour gagner des prix parrainés par l'industrie pour les meilleures présentations de la conférence.

**Soumission d'articles** – L'échéance pour la soumission des résumés est le 15 Juin 2012. Les résumés de deux pages pour publication dans le numéro d'actes de conférence d'*Acoustique Canadienne* sont dus pour le 1er août 2012. Les détails seront donnés sur le site internet de la conférence

**Inscription** – Les détails sur les frais et formulaires d'inscription seront bientôt disponibles sur le site internet de la conférence. La pré-inscription à prix réduits est disponible jusqu'au 5 septembre 2012 et est fortement encouragée.

## Comité d'Organisation

- Président de la conférence: Stan Dosso sdosso@uvic.ca
- Président scientifique: Roberto Racca roberto.racca@jasco.com
- Trésorerie et inscription : Clair Wakefield clair@wakefieldacoustics.com
  Lori Robson lori@wakefieldacoustics.com
- Site internet : Brendan Rideout brendan.rideout@gmail.com
- Logistique : Lisa Cooper lisa.cooper@jasco.com
- Exposition technique: Rich Peppin peppinr@verizon.net

## *ACOUSTICS WEEK IN CANADA / SEMAINE CANADIENNE D'ACOUSTIQUE*
## *QUEBEC CITY 12-14 OCTOBER/OCTOBRE 2011*
## *PRIZE WINNERS*

***BELL Prize Winner***
***Martin Brummund***
***(Ecole de technologie supérieure)***

***Student Presentation Award Winners***
***Sonal Bhadane (Ryerson University)***
***and***
***Guilhem Viallet***
***(École de technologie supérieure)***

## The Canadian Acoustical Association / l'Association Canadienne d'Acoustique

# MEMBERSHIP DIRECTORY 2011 / ANNUAIRE DES MEMBRES 2011

The number that follows each entry refers to the areas of interest as coded below.
Le nombre juxtaposé à chaque inscription réfère aux champs d'intérêt tels que condifés ci-dessous

| Areas of interest | | Champs d'intérêt |
|---|---|---|
| Architectural Acoustics | 1 | Acoustique architecturale |
| Engineering Acoustics / Noise Control | 2 | Génie acoustique / Contrôle du bruit |
| Physical Acoustics / Ultrasonics | 3 | Acoustique physique / Ultrasons |
| Musical Acoustics / Electro-acoustics | 4 | Acoustique musicale / Electroacoustique |
| Psycho- and Physio-acoustics | 5 | Psycho- et physio-acoustique |
| Shock and Vibration | 6 | Chocs et vibrations |
| Hearing Sciences | 7 | Audition |
| Speech Sciences | 8 | Parole |
| Underwater Acoustics | 9 | Acoustique sous-marine |
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## INSTRUCTIONS TO AUTHORS FOR THE PREPARATION OF MANUSCRIPTS

**Submissions:** The original manuscript and two copies should be sent to the Editor-in-Chief. The manuscript can also be submitted electronically.

**General Presentation:** Papers should be submitted in camera-ready format. Paper size 8.5" x 11". If you have access to a word processor, copy as closely as possible the format of the articles in Canadian Acoustics 39(1) 2011. All text in Times-Roman 10 pt font, with single (12 pt) spacing. Main body of text in two columns separated by 0.25". One line space between paragraphs.

**Margins:** Top - 0.75"; bottom - 0.75" minimum; sides - 0.75".

**Title:** Bold, Times New Roman 14 pt with 14 pt spacing, upper case, centered.

**Authors/addresses:** Names and full mailing addresses, 10 pt with single (12 pt) spacing, upper and lower case, centered. Names in bold text.

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**Line Widths:** Line widths in technical drawings, figures and tables should be a minimum of 0.5 pt.

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**Page numbers:** In light pencil at the bottom of each page. For electronic submissions, do not number pages.

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