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Hearing Aid Use in Noisy Workplaces

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In compliance with IRSST policy, the research results published in this document have been peer-reviewed.

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SUMMARY

Noise is a constant presence in the workplace. As a result, many workers live with occupational hearing loss. Others may have hearing loss of non-occupational origin, while an aging workforce is at greater risk of suffering from hearing loss. Hearing loss can compromise the effective realization of tasks and the safety of workers and others when it is accompanied by difficulties in perceiving audible signals, including speech, in noisy surroundings, and the ability to identify where sounds are coming from. To maintain an accurate perception of ambient sound and to do their jobs safely, effectively and autonomously, a possible solution for workers with hearing loss could be to wear hearing aids. However, there are important questions as to whether hearing aids can actually optimize the hearing abilities needed by workers to carry out their tasks and to amplify useful sounds to safe levels without exacerbating the loss.

Few scientific studies have dealt with the issue of wearing hearing aids in noisy work environments. We therefore know very little about the practice and the associated risks and benefits. This study involved a quest for information from health professionals, workers and manufacturers, as well as a review of the scientific literature. Its aim was to (1) explore the occurrence of hearing aid use in noisy workplaces; (2) examine the risk of aggravating hearing loss in workers who wear hearing aids in noisy work environments and to establish valid measurement methods to assess the risks of over-amplification; (3) determine whether hearing aids can be used to support hearing and communication needs without aggravating hearing loss or compromising safety, and to (4) establish whether other amplification and protection technologies (e.g., sound restoration hearing protection devices) could help improve hearing performance at work, or at least not worsen it.

While the study was unable to precisely determine the number of workers who use hearing aids in noisy work environments, many health professionals report having seen, at least once in the past five years, a worker who was using them in a noisy environment, or a worker who was considering the possibility of doing so. Among the obstacles to adequate management of these cases, a lack of valid methods to measure the risk of over-amplification, clear guidelines, and consultation and collaboration mechanisms among the various professionals involved are reported. Information sharing among professionals with respect to context and sound levels, the demands of the workstation and viable solutions is especially limited. The role of each professional is not well understood, which does not encourage interdisciplinarity. In most cases, professionals attempt to preserve workers' residual hearing by discouraging hearing aid use in noisy work environments, but in so doing, they may be underestimating these workers' need to hear, in terms of efficiency, safety and communication.

A review of the literature, including that dealing with current technologies, did not lead to definitive conclusions about the risk of aggravating hearing loss by hearing aid use, or to the determination of a valid, reliable and standardized method to document or predict this risk. In fact, recommendations for workers remain quite limited and are generally not supported by evidence.

Besides over-amplification, health professionals are also concerned that hearing aids could compromise workers' safety by reducing some of the hearing capacity necessary for the autonomous and safe execution of tasks in the workplace. Depending on how parameters are adjusted, there may be a decrease in speech comprehension in the presence of noise when hearing aids are worn compared to without them. Some adjustments can, however, contribute to

improving this capacity in some situations, such as the use of directional microphones that amplify the sources of sound placed directly in front of an individual more than those behind him or her, while others, such as noise reducers, contribute to improving the comfort of hearing and sound quality, while reducing the effort required to hear. The scientific literature is less conclusive on how well hearing aids help wearers localize where sounds are coming from, but in general, performance is better without them. Scientific data do not clearly demonstrate that hearing aids contribute to improving the required hearing capacity, both for the autonomous execution of work tasks and for ensuring the safety of workers with hearing loss. On the other hand, these data do not enable us to say with certainty that hearing aid use represents a risk for workers' safety.

A review of alternative or additional options to wearing hearing aids is therefore necessary. Despite some remarkable technological advances in the area of active hearing protection and their generally positive reception by workers, a device to systematically improve hearing capacity does not appear to exist. Furthermore, there are fewer possibilities of adapting and personalizing hearing protectors' adjustment compared to hearing aids. It is also difficult to select a product adapted to the needs of workers with hearing loss and to the workplace because manufacturers' accessibility is limited in terms of parameters and the operation of their products. A possible explanation for this is the absence of standards for test conditions, the parameters to be assessed and the information that should be included in the technical specifications for active hearing protectors. These elements, in addition to the safety aspect, require further study in terms of their contribution before systematically suggesting their use for workers with hearing loss.

For this study, the research team advocates the precautionary principle, by recommending that hearing aid use only be considered as a last resort, after first looking into reducing noise in the workplace and other avenues, such as modifying the hearing, communication and localization requirements at the workstation and adapting it to include another sensory modality (vibrating or visual cues). It is essential that the risk of over-amplification and worker safety be taken into account and managed by all of the professionals concerned. In the absence of clear, evidence-based guidelines, it is even more important for professionals to consult, coordinate and work together to make the most appropriate recommendations in response to the objective of not compromising the health and safety of workers and others.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three dimensions
AGC-O	Automatic gain control- output
AGC-I	Automatic gain control- input
ANR	Active noise reduction
ANSI	American National Standards Institute
ASA	Acoustical Society of America
B&K	Brüel & Kjaer
BDSP	Banque de données de santé publique (public health data base)
BILL	Bass increase at low levels
BTE	Behind the ear (hearing aid)
CIC	Completely in the canal (hearing aid)
CINAHL Plus	Cumulative Index to Nursing and Allied Health Literature
CLSC	Centre local de services communautaires (local community service centre)
CNESST	Commission des normes, de l'équité, de la santé et de la sécurité du travail (Québec's labour standards, equality and occupational health and safety board)
CSA	Canadian Standards Association
CSST	Commission de la santé et de la sécurité du travail[1]
dBA	A-weighted decibels
dB HL	Decibel, Hearing Level
dB SPL	Decibel, Sound Pressure Level
DSL	Desired sensation level
ATTS	Asymptotic temporary threshold shift

[1] **On January 1, 2016, the CSST became the CNESST, the Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST).**

PTS	Permanent threshold shift
TTS	Temporary threshold shift
TTS_2	Temporary threshold shift measured two minutes after exposure
HA-1	Hearing aid coupler
HA-2	Hearing aid coupler
HSE	Health & Safety Executive
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE Xplore	Institute of Electrical and Electronics Engineers Digital Library
ENT	Ear, nose and throat specialist
INSPQ	Institut national de santé publique du Québec (public health institute)
NRR	Noise reduction rating
IRSST	Institut de recherche Robert-Sauvé en santé et en sécurité du travail du Québec
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LAeq	Equivalent sound level
LAmn	Mean LAeq in situ
$L_{ex, 8h}$	Daily exposure-vibration, normalized to an 8 hour reference period
MEDLINE	Medical Literature Analysis and Retrieval System Online
FM	Frequency modulation
CRIR	Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain (Greater Montréal interdisciplinary rehabilitation centre)
MIRE	Microphone in a real ear
MPL	Modified power law
MPO	Maximum power output

NAL-R	National Acoustic Laboratory- Revised
NRR	Noise reduction rating
NRSA	Noise reduction statistics for A weighting
WHO	World Health Organization
OOAQ	Ordre des orthophonistes et audiologistes du Québec
OSHA	Occupational Safety and Health Administration
HA	Hearing aid
Pubmed	Search engine
RAMQ	Régie de l’assurance maladie du Québec
RECD	Real-ear-to-coupler-difference
Scopus	Scopus database
OHS	Occupational health and safety
TILL	Treble increase at low levels
Web of Science (ISI)	Institute for Scientific Information

1. INTRODUCTION

Every year, many workers exposed to noise develop hearing loss. In fact, in every year from 1997 to 2010, the Commission de la santé et de la sécurité du travail (CSST) in Québec recognized occupational hearing loss in almost 2600 workers (Institut national de santé publique du Québec, 2014). Hearing loss begins insidiously over the years and causes problems such as difficulties in perceiving sound, understanding speech, and the ability to adjust the volume of one's voice and to localize sound sources. These difficulties are experienced not only at home and during leisure activities, but also at work. In the context of the workplace, diminished hearing ability justifies raising questions about its consequences on these workers' safety and their ability to perform their duties effectively. Not hearing a sound warning, a verbal command or being unable to localize where a backup alarm is coming from, for example, could lead to serious and even deadly accidents (Deshaies et al., 2008, 2015).

To optimize workers' hearing and communication abilities, hearing aids may be viewed as a solution. However, hearing aids are designed and adjusted to maximize the speech perception in environmental conditions that may differ greatly from noisy and echoing workplaces that make it difficult to localize where sounds are coming from. Health professionals do not generally recommend their use in noisy work environments, mainly because of the fear of provoking an overexposure to noise (caused by amplification of sound or an input signal that is too high), which could aggravate hearing loss or create dangerous situations for the workers. Few studies have dealt with this issue, which concerns both hearing health and the occupational safety of those suffering from occupational hearing loss or other etiologies.

This study thus aims to establish the state of knowledge of hearing aid use in noisy workplaces. The noisy environments considered in the study are not limited to those in which sound levels are over the regulated limits (85 or 90 dBA, depending on the jurisdiction); they also include those in which sound levels are lower (≥ 70 dBA), but where hearing aid use could potentially cause over-amplification. The preliminary step of seeking information from health professionals, manufacturers and a survey of scientific literature is crucial to determine whether (1) hearing aids could be used to support hearing, communication and localization needs without aggravating hearing loss or compromising safety, and whether (2) other amplification and protection technologies (e.g., sound restoration hearing protection devices) could help improve hearing performance at work, or, at least, not cause it to worsen.

2. STATE OF KNOWLEDGE AND RESEARCH OBJECTIVES

2.1 State of Knowledge

Millions of workers are exposed to dangerous noise levels in their workplaces every day, and many of them develop occupational hearing loss (WHO, 2000). In 2007–2008, it was estimated that approximately 287,000 to 359,000 workers in Québec were regularly or constantly exposed to industrial noise at sound levels sufficiently loud enough to interfere with communication at a distance of a few feet, even if they were shouting (INSPQ, 2014). In addition, in every year from 1997 to 2012, the CSST recognized occupational hearing loss in more than 2800 workers (INSPQ, 2015).

According to the model proposed by Hétu (1994), noise in the workplace leads to hearing loss, reduced performance, annoyance, stress, additional effort in attention and concentration and interference with communication. The effects increase the risk of fatal accidents in the workplace (Deshaies et al., 2008, 2015). While noise is not often reported as a directly contributory factor in workplace accidents, Deshaies et al. (2008) analyzed 788 fatal accident investigation reports by the CSST and determined that noise was a causal factor in 2.3% of the cases. Given the methodological limitations (such as a lack of access to the handwritten inspectors' reports, incomplete data in certain reports, analysis of fatal accidents only), that percentage probably underestimates the proportion of fatal accidents related to noise in the workplace. Moreover, the financial and human cost associated with these fatal accidents is certainly not insignificant (Lebeau et al., 2014).

Accidents can occur for a number of reasons: a signal was not heard, or no attention was paid to it, a signal was not recognized, or it was not known where it was coming from. Locating and interpreting a sound signal are two difficulties often reported by workers suffering from hearing loss (Trottier et al., 2004). Because hearing loss can compromise these abilities, some studies have associated it with an increased risk of accident (Wilkins et Acton, 1982; Zwerling et al., 1997; Picard et al., 2008; Deshaies et al., 2008, 2015; Girard et al., 2009, 2014).

Occupational hearing loss begins insidiously and cannot be corrected medically. The solution often contemplated to facilitate communication for people affected is the use of hearing aids. While these devices amplify sound, they do not provide normal functional hearing in workers and do not guarantee improvement in speech perception, particularly in the presence of background noise (Bray et Nilsson, 2008), or the ability to locate sound (Van den Bogaert et al., 2006; Vaillancourt et al., 2011). Thus, recommending that workers exposed to noise wear hearing aids poses a major dilemma. For some, perception, recognition and ability to locate a sound signal or speech are essential: their inability to do so in certain situations could not only increase their workload and decrease their autonomy, but could compromise their safety or that of their coworkers. For example, in a clinical setting, workers reported wanting to wear their hearing aids so that they would be able to detect the warning signals of a machine malfunction to avoid damage (changes in machine rotation noise, sounds related to a production line jam), and to perform their tasks more effectively. However, clinicians do not generally recommend wearing hearing aids in a noisy workplace because of the potential risk of aggravating the hearing loss through over-amplification caused by a too powerful gain or input signal (Dolan and

Maurer, 2000; OOAQ, 2000). However, other administrative (e.g., limiting exposure time), organizational (e.g., changing a task to eliminate the need to hear a given signal) or technological (e.g., controlling noise at its source) recommendations could be formulated.

The fundamental issues that concern health professionals (audiologists, hearing aid dispensers, attending physicians [otorhinolaryngologists (ENT specialists), general practitioners], occupational nurses and physicians) include (1) over-amplification; (2) effectiveness of hearing aids in supporting listening, communication and localizing sound sources in the typical acoustic conditions of the workplace (ambient noise, reverberations, moving and multiple sources of noise, noise direction, wearing of diverse protection equipment); (3) the optimal parameters to consider when hearing aids are adjusted (e.g., maximum output, automatic gain control, noise reduction algorithms, etc.) and 4) the potential attenuation provided by wearing a hearing aid that is not turned on. The Ordre des orthophonistes et audiologistes du Québec (OOAQ) raised these issues in a letter of support sent to the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) in January 2010. The concerns of professionals with respect to hearing aid use in noisy workplaces are not limited to Québec. Some groups (such as EUHA 2013) have developed guidelines for their members. However, these guidelines are very general (e.g., verification of the earmold seal, need to ensure communication, to control the output of the device to a maximum of 85 dBA, compatibility with wearing protectors, etc.) and do not provide specific methods for adjusting the devices. Given the aging population and the abolition of obligatory retirement at 65, and the proportional relationship between age and the progression of hearing loss, the number of people in the workplace with hearing loss is sure to grow significantly in the coming years. It is to be expected that the risk of accidents related to hearing loss will also increase. Evidence-based provisions and practices are necessary to ensure the better health and safety of workers in noisy environments.

Today, knowledge in this area is still limited and no study appears to have clearly addressed the issues. However, we note increased interest from hearing aid manufacturers to improve their products' performance by targeting the accurate reproduction of important indicators (temporal and spatial) used by the auditory system to operate in the complex environments of daily life (Neher et al, 2008; Behrens, 2008). In addition to hearing aids, other technologies that aim to both lower exposure to noise and the amplification in a noisy environment have been suggested, for example, "smart" earplugs or active protectors, including protectors with an integrated communication system and sound restoration hearing protection devices (CSA Z94.2-F14). While these devices seem promising, they are not well regulated by national or international standards that would enable their characteristics and acoustic performances to be documented, unlike hearing aids (e.g., ANSI/ASA S3.22-2009).

Given the high number of potential users (i.e., workers suffering from occupational hearing loss and a progressively aging workforce), emerging technologies and the increased risk of accidents in noisy workplaces, a serious examination of the issues is both relevant and a priority. It was necessary to first document the practice and tools now available or used by health professionals. The study aims to identify the state of knowledge through reviews of the literature and requests for information from health professionals and manufacturers of hearing protectors equipped with specific devices and hearing aids. The study targets several priority research areas of the IRSST, i.e., communication in noisy environments, improvement and development of equipment better adapted for use in the workplace, design of intervention models to foster safe and sustainable work practices and finally, the aging population and its effects on occupational health and safety (OHS).

2.2 Research Objectives

The general objective of this study is to verify whether hearing aids can be used to reduce hearing, communication and localization problems in noisy work environments without aggravating hearing loss or compromising people's safety, and if other amplification and protection technologies (e.g., sound restoration hearing protection devices) could help maintain or improve hearing performance at work. More specifically, the study is divided into four distinct phases to take stock of the use of hearing aids in a noisy environment:

Phase 1: Explore the occurrence of hearing aid use in noisy work environments in Québec, the practices and tools used by health professionals, and the needs expressed by workers;

Phase 2: Examine the risk of aggravating hearing loss in workers who wear hearing aids in noisy workplaces, and establish valid measurement methods to evaluate the risks of over-amplification;

Phase 3: Review knowledge about the effect of auditory amplification on speech perception in a noisy environment and on sound localization;

Phase 4: Review knowledge about new active hearing protectors, in particular, sound restoration hearing protection devices that can facilitate hearing, communication and localization, while limiting exposure to noise.

Each of these phases is the subject of a chapter in this report (chapters 3 to 6). In each of these chapters, we discuss the objective of the phase, the methodology used to reach it, the results obtained and a brief discussion. Chapter 7 presents a general discussion to review and take stock of the knowledge, the practices and options offered to hard-of-hearing workers who work in noisy workplaces, as defined in the terms of the study. Finally, the conclusion suggests what further action can be taken after this preliminary study to respond to the concerns of the principal stakeholders concerned by the issue.

3. WEARING HEARING AIDS IN A NOISY WORK ENVIRONMENT—PORTRAIT OF PRACTICES AND NEEDS (PHASE 1)

3.1 Objective

In this phase, we attempted to identify the scope of the issue (the number of workers concerned and their profiles, the type of workplace, the number and types of requests received by health professionals in terms of amplification in noisy environments) and to describe current practices and tools used by these professionals to respond to the needs of workers who would benefit from amplification in a noisy workplace (clinical practices, products used, alternatives to hearing aids or recommended accommodations, etc.).

3.2 Methodology

Different means were used to study the issue: (1) a literature review completed in September 2012; (2) an online questionnaire for the various professionals concerned and (3) focus groups with professionals and workers.

3.2.1 Literature Review

At the start of the study, a literature review was completed using various databases (Banque de données en santé publique (BDSP), CINAHL Plus, Pubmed, MEDLINE, Web of Science (ISI)). The following keywords were used: "hearing aids" and "workplace," "hearing aid use" and "industrial noise," "hearing aid use" and "noisy workplace," "hearing aid use" and "occupational audiology," "hearing aid use" and "noise exposed workers," "hearing aid fitting" and "occupational noise," "hearing aid fitting" and "guidelines," "hearing aids in noise" and "guidelines," "hearing aids" and "industrial audiology," "fitting of hearing aids" and "noisy workplace," "hearing aid fitting" and "workers," "hearing aid dispenser" and "noisy workplace" or "industrial noise" or "industrial audiology" or "rehabilitation of noise exposed workers," "hearing aid fitting" and "rehabilitation of noise exposed workers," "hearing aid" and "occupational audiology."

3.2.2 Online Questionnaire

To discover whether hearing aid use in noisy workplaces is a common occurrence dealt with by the various health professionals consulted, they were given a questionnaire (Appendix A). ENT specialists, audiologists, hearing aid dispensers and professionals (physicians and nurses) from the Réseau de santé publique en santé au travail (Québec's public health network for occupational health) were asked to fill out the online questionnaire. They were invited through their professional association, which has a representative in this study's follow-up committee. For the professionals in the local occupational health teams (the physicians responsible and nurses), their coordinator was asked by email to invite them to complete the questionnaire.

The questionnaire, accessible online on the SurveyMonkey website, contained some 20 questions, which included some to gather demographic data about the respondents, their professional experiences and the administrative regions in which they work. The questions to learn how often the issue occurs were presented in the form of scenarios describing situations featuring a worker and hearing aids. The respondent was to indicate whether they had experienced such situations. If they had, they indicated the number of times in which the situation had occurred over the past five years and the industrial sectors in which it occurred. The box below contains the various scenarios proposed.

Have you ever been faced with the following situation: a worker with hearing loss, of any nature, degree or origin…

Scenario 1

… who intends to use or who is wondering about using his/her hearing aids in a noisy workplace? (question 8)

Scenario 2

… who uses his/her hearing aids in a noisy workplace? (question 11)

Follow-up question related to scenario 2

Among workers who use their hearing aids in noisy workplaces, do you know if any of them are required to use them by their employer? (question 14)

Scenario 3

… who does not use his/her hearing aids in a noisy workplace, even though a health professional recommends their use or the employer requires it? (question 16)

Scenario 4

…who does not use his/her hearing aids, but who can use another electronic amplification device (FM system, hearing protector with integrated communication system or another electronic protector? (question 19)

At the end of the questionnaire, the respondents could indicate their interest in participating in a focus group on the subject, and if they were interested, they could leave their contact information. They were offered the option of sending their contact information by email, in order to guarantee the confidentiality of their responses to the questionnaire. The questionnaire was accessible online from October 3, 2012 to February 18, 2013.

3.2.3 Focus Groups

Between May 7, 2013 and April 9, 2014, seven focus groups were organized: five with professionals and two with workers. It was not possible to organize a meeting with the ENT specialists. Altogether, 35 people, including two union representatives, participated. Table 1 provides the dates, locations and number of participants at these discussions.

The meetings were facilitated by at least one researcher, often two, and one of the team members was responsible for taking notes. The meetings, which lasted between 90 and 120 minutes, were recorded (audio only) to help with drafting the minutes. The objectives of the research and the encounter were presented first, with as a summary of the questionnaire results. A consent form, approved by the ethical committee of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montréal (CRIR) and by the Office of Research Ethics and Integrity of University of Ottawa, was provided to participants who signed. If needed, a question period preceded the beginning of the discussion.

Table 1 – Dates, locations, participants (profession, practice location) and number of focus groups

Dates and locations	Participants	Number
May 7, 2013 Montréal	**Audiologists** Montréal, Montérégie, Côte-Nord, Chaudière-Appalaches	5, including 2 by Skype[2]
May 15, 2013 Québec	**Audiologists** Chaudière-Appalaches, Bas-Saint-Laurent, Québec, Gaspésie-Îles-de-la-Madeleine	5, including 1 by videoconference
September 13, 2013 Montréal	**Hearing Aid Dispensers** Montréal, Gaspésie-Iles-de-la-Madeleine, Abitibi-Témiscamingue, Estrie	4
October 28, 2013 Longueuil	**Occupational health** Montérégie	6 nurses
November 13, 2013 Sherbrooke	**Occupational health** Centre-du-Québec, Estrie	5, including 1 by videoconference (4 nurses, 1 physician)
November 18, 2013 Drummondville	Workers who **do not use** their hearing aids at work	6 (4 + 2 union representatives)
April 9, 2014 Longueuil	Workers who **use** their hearing aids at work	4

[2] http://www.skype.com/en/

3.2.3.1 Focus Groups with Hearing Health Professionals

The professionals encountered had to have at least two years of experience with workers to participate. The invitations were sent out by email. The meetings were organized in order to reach the greatest number of participants (schedule, location, or remote access by Skype or videoconference). The objective of discussions with the professionals was to examine the issues related to the context in which they interacted with the workers. Their participation enabled us to better understand the extent of their responsibilities and the factors that determined their actions. During these meetings, the perception of their role in the decision to use or not use hearing aids in noisy workplaces was also explored.

A set of questions guided how these meetings were conducted. It was slightly adapted according to the type of professionals encountered.

1. What brings workers to your office?
2. What are the procedures, protocols or tools you use to respond to workers' needs or to assess the situation you are presented with?
3. In your opinion, who should assess the relevance of using hearing aids in noisy workplaces?
4. What influences how you manage the situation?
5. What recommendations do you make to workers or for the workplace?
6. Do you feel you are sufficiently equipped to make informed recommendations about wearing hearing aids in noisy workplaces?
7. Are there obstacles restricting your actions with this clientele?
8. What types of tools, protocols or collaboration would help you better manage the issue of hearing aid use in noisy workplaces?

3.2.3.2 Focus Groups with Workers

The workers who participated in the focus groups were recruited with the help of the members of the follow-up committee. They contacted union representatives, who in turn contacted workers who use hearing aids and assessed their interest in participating in a focus group on the subject. The representatives then contacted a member of the research team to organize the encounters with them. This resulted in two meetings to talk with the workers (three women and five men) who wore hearing aids. Some did not wear their hearing aids at work (n=4) while others did (n=4). Five of the workers had received compensation from the CSST for occupational hearing loss, while the three others wear hearing aids because of hearing loss due to a reason other than solely occupational (e.g., mixed loss or sensorineural hearing loss at birth). The participants came from three different companies situated in the Montérégie and the Centre-du-Québec regions.

The meetings with the workers took place in basically the same way as with those of the various hearing health professionals. However, some of the questions they were asked focused more on their experience with hearing aids, the process that led to them wearing them and their opinions about hearing aid use in noisy work environments. The following are the questions asked of the workers:

1. Why do you wear (or do not wear) your hearing aids at work?

2. Do you know of other workers who wear hearing aids in noisy workplaces, or workers who would like to wear them, but who decided not to?

3. How do you use your hearing aids at work?

4. For those who do not wear hearing aids at work, have you ever tried, or thought of a way of wearing them (in light of the previous question)?

5. Do you use any devices other than your hearing aids to help you to hear better or to communicate in noisy conditions?

6. What was the process that led to you making the decision to use (or not to use) hearing aids in your workplace?

7. If you have seen one or more professionals, have they made any specific recommendations for the use of hearing aids in noisy workplaces?

8. Are you satisfied with the recommendations that you got about wearing hearing aids in noisy workplaces?

9. Whether you wear or do not wear your hearing aids, are you worried about your physical health and the safety of your hearing?

For the union representatives present who had known of the workers' intention to use their hearing aids in the workplace: (1) Who have they seen to assist them in making their decision? (2) Have you ever been contacted by health professionals who want to know more about the work environment of a specific worker?

3.3 Findings

3.3.1 Literature Review

The literature review resulted in the retrieval of 35 documents. However none of the documents consulted contained specific information about the occurrence of hearing aid use in noisy workplaces. One study mentioned that a questionnaire given to 445 hard-of-hearing workers (Verbsky, 2002) asked about this practice. However, no information was reported with respect to it. In response to an email addressed to the researchers, they confirmed that no particular compilation related to that issue had been made. In another study (Williams et al., 2006) carried out with active and retired workers and reporting on hearing disabilities (i.e., 9% of the 10 respondents to the survey), 33% mentioned that wearing hearing aids in the workplace was or had been part of their way of dealing with their hearing difficulties. There was no information that could make it possible to relate this practice to the noise levels in those workplaces.

In all, ten documents provided information deemed relevant to understanding the issue. These documents are included in the bibliography. The authors suggest that workers who habitually wear hearing aids tend to also want to use them at work (Laplante-Lévesque et al., 2010; Verbsky, 2002) because they think they help them communicate better with their coworkers, increase the probability of hearing the noises made by machines and alarms, and provide them with greater ability to localize sound sources (Chalupka, 2009; Witt, 2007). Some workers mention their fear of physical injuries to explain their use of hearing aids in the workplace (Dolan and O'Loughlin, 2005). It should be noted that this same fear is evoked by workers to explain their choice of not using ear protectors when they are exposed to noise (Verbsky, 2002), out of fear that the noise protection would prevent them from hearing sound signals that they feel they need to hear for their safety.

The necessity of determining whether hearing aids can be used in noisy workplaces, and, to that end, developing assessment protocols, is urgent when we consider that workers aged 65 and over constitute an increasingly greater proportion of the active labour force (Fok et al., 2009; Williams et al., 2006). It has been estimated that in 2012, in the United States, 40 million workers had reached that age, and among them, 33.4% had hearing loss, 10.2% had vision loss and 38% had sensory losses in both vision and hearing (Davila et al., 2009). In Canada, it is anticipated that the proportion of workers aged 65 and over will reach 22.6% in 2022, compared to 17.7% in 2012.[3] It is also estimated that over 50% of Canadians aged 65 and over have hearing loss (Public Health Agency of Canada, 2010).

We note that there is little documentation in the scientific literature about the phenomenon of hearing aid use by workers in noisy workplaces. To try to learn more about the practice, the team addressed hearing health professionals who practice in Québec and asked them to complete a questionnaire about the issue.

3.3.2 Online Questionnaire

Altogether, 218 people participated in the survey and 198 completed the questionnaire. Among the respondents, the proportion of audiologists and occupational health professionals is the highest. These two groups represent slightly more than two thirds of the respondents. The other third is made up of hearing aid dispensers and ENT specialists. Figure 1 shows the proportion of respondents by profession.

[3] Canadian Occupational Projection System: http://professions.edsc.gc.ca/sppc-cops/c.4nt.2nt@-eng.jsp?cid=51

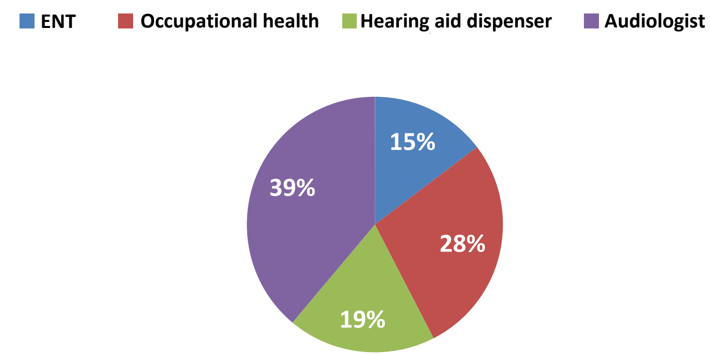

Figure 1 – Proportion of respondents according to their profession (N=198)

Table 2 provides details regarding this distribution, and includes the total number of those employed in these professions in Québec. That information is provided for informational purposes only, because the professionals who do not count adult workers among their clientele and who do not feel affected by the questionnaire were not removed from the total numbers. Of course, in the case of occupational health professionals, workers are their target clientele. The majority of respondents in that category are nurses: 46/55 respondents. The last column in the table indicates the number of professionals with at least two years of experience working with workers such as those who said they were interested in participating in a focus group. The application of this inclusion criterion for participation in the focus groups reduced the number of potential participants from 59 to 48.

Table 2 – Distribution of respondents by profession. The total workforce in Québec for each of the professions is noted between parentheses

Potential participant (Workforce in Québec, April 2014)	Number	Agreed to participate in a focus group	Provided contact information	Professional experience ≥ 2 years
ENT (209)	29	7	4	4
Occupational health (255)**	55	15	15 + 2 *	15
Hearing aid dispenser (327)	37	13	11 + 1 *	10
Audiologist (393)	77	31	25 + 1 *	19
Total	**198**	**66**	**55 + 4 ***	**48**

*People who sent their contact information by email. **Counted at the end of 2012.

The respondents to the questionnaire came from all over Québec. The regions of Montérégie, Montréal and Estrie (Eastern Townships), have the greatest representation. Region 10, Nord-du-Québec, was the only region with no respondent. Table 3 shows the regions where these professionals work. A single respondent may be active in more than one region, which is why there is a higher number for all the regions than the total number of participants (224 compared to 198). The occupational health professions had the fewest respondents working in several regions. The number of people who stated they were interested in participating in the focus groups and where they are from is indicated between brackets in each of the columns. To reflect the exact number of people interested in participating, their provenance is indicated only on the line corresponding to the region associated with their professional email, telephone number, or primary address, as indicated in the available telephone directories.

The responses to the questions regarding the scenarios made it possible to identify whether hearing aid use in noisy workplaces is frequent or marginal.

Question 8 (scenario 1): *Have you ever been faced with the following situation: a worker with hearing loss, of any nature, degree or origin, who* ***intends to use or who is wondering about using*** *his/her hearing aids in a noisy workplace?* **84%** of respondents stated that they had faced this situation at least once in the past five years. Figure 2 shows the distribution of responses by profession. These findings reveal that most professionals who responded to the questionnaire have been in contact, at least once, with a worker who was wondering about wearing hearing aids in a noisy workplace. While half of the professionals reported having experienced such a situation between one and ten times over the past five years, one third reported having been faced with it more than ten times during the same period. Hearing aid dispensers were the group who reported facing this situation the most often.

Table 3 – Provenance of respondents to the questionnaire and those who agreed to participate in the focus group and who left their contact information, by profession

Region	ENT	Occupa-tional health	Hearing aid dispenser	Audiologist	Total	Agreed to participate in focus groups
Bas-Saint-Laurent (01)	1		1	5 [2]	**7**	**2**
Saguenay–Lac-Saint-Jean (02)	1	3	2 [1]	3 [1]	**9**	**2**
Québec City (03)	3	5 [1]	4 [2]	4 [4]	**16**	**7**
Mauricie (04)	1			2	**3**	**0**
Estrie (05)	2	7 [4]	3 [2]	8 [1]	**20**	**7**
Montréal (06)	7 [1]	3 [1]	9 [3]	19 [4]	**38**	**9**
Outaouais (07)	1 [1]		3 [1]	5 [2]	**9**	**4**
Abitibi-Témiscamingue (08)	2	4	4 [2]	3	**13**	**2**
Côte-Nord (09)			1	3 [2]	**4**	**2**
Nord-du-Québec (10)					**0**	**0**
Gaspésie–Îles-de-la-Madeleine (11)	1		1	3 [1]	**5**	**1**
Chaudière-Appalaches (12)	2	6 [1]	1	3 [2]	**12**	**3**
Laval (13)	2		2	3	**7**	**0**
Lanaudière (14)	3 [1]			4	**7**	**1**
Laurentides (15)	2	3	7 [1]	8 [3]	**20**	**4**
Montérégie (16)	2 [1]	23 [9]	4	18 [2]	**47**	**12**
Centre-du-Québec (17)		2 [1]	2	3 [2]	**7**	**3**
Totals by profession	**30* [4]**	**56 [17]**	**44 [12]**	**94 [36]**	**224**	**59**

*A respondent may work in several administrative regions, which is why the total number (224) is higher than the number of participants (198).

[ ] Number of respondents who agreed to participate in focus groups and who left their contact information.

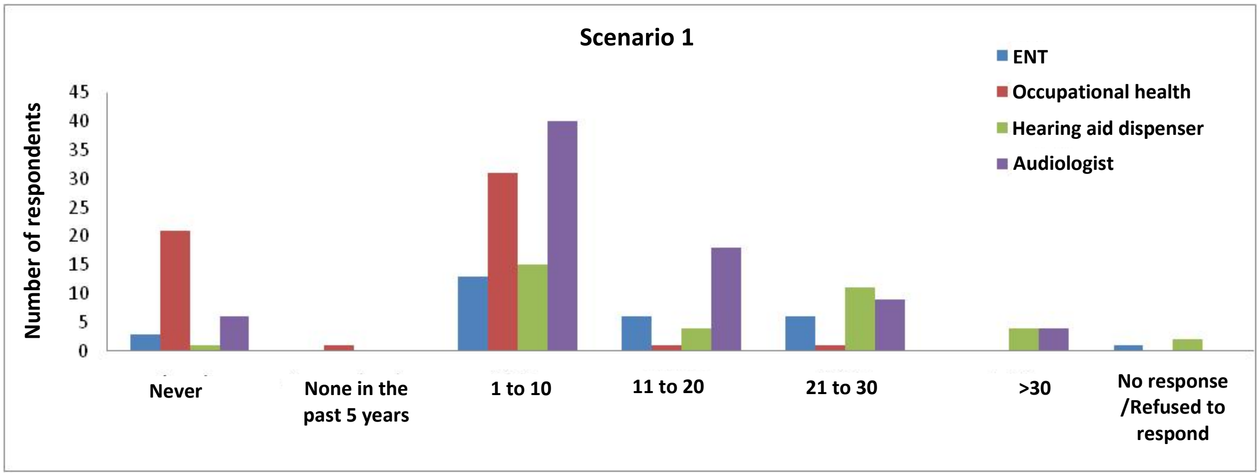

Figure 2 – Number of respondents who, over the past five years, observed that a worker intended to use or was wondering about using hearing aids in a noisy workplace

Question 11 (scenario 2): *Have you ever been faced with the following situation: a worker with hearing loss, of any nature, degree or origin,* ***who uses*** *his/her hearing aids in a noisy workplace?* Almost 2/3 (**63%**) of respondents stated that they had faced such a situation at least once. Figure 3 shows the distribution of responses by profession. The majority of professionals questioned, or two thirds of them, reported that they had seen a worker who used hearing aids in a noisy workplace. Almost half of these respondents recounted that they had experienced the situation between one and ten times over the past five years, and 12% had experienced it more than ten times over the same period. Hearing aid dispensers reported that they had seen the situation the most frequently, followed by ENT specialists.

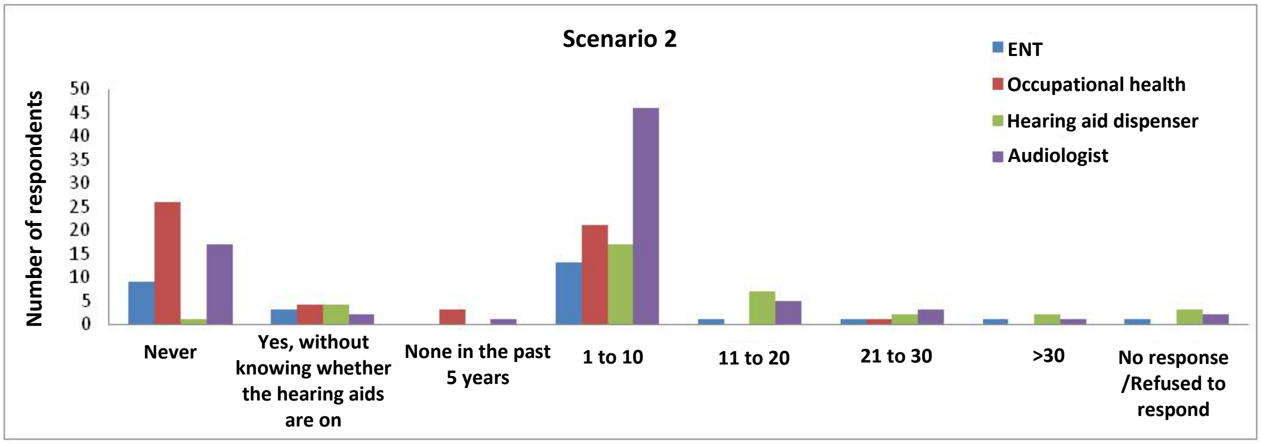

Figure 3 – Number of respondents who, over the past five years, observed that a worker was using hearing aids in a noisy workplace

Question 14 (follow-up question): *Among workers* ***who use*** *hearing aids in noisy workplaces, do you know if any of them* ***are required*** *to use them by their employer?* This question aims to clarify the previous response dealing with the scenario of workers who use hearing aids. It was only provided to respondents who reported that they had faced the situation, or 132 respondents. Half of them (50%) indicated that the employer did not require workers to use hearing aids.

Among the other half, a sizeable proportion, or 40%, stated that they did not know whether or not hearing aid use was required by the employer. Table 4 illustrates the distribution of responses according to professions.

Table 4 – Distribution of the responses of respondents who observed workers using hearing aids in noisy workplaces in terms of whether or not the employer required it

Participants	YES	NO	Don't know
ENT (17/29)	1	10	6
Occupational health (28/55)	4	13	11
Hearing aid dispenser (31/37)	1	19	11
Audiologist (56/77)	7	24	25
Total (132/198)	13 (10%)	66 (50%)	53 (40%)

Question 16 (scenario 3): *Have you ever been faced with the following situation: a worker with hearing loss, of any nature, degree or origin who* ***does not use*** *his/her hearing aids in a noisy workplace* ***even though a health professional recommends their use*** *in or the employer requires it?* Almost a quarter of the respondents (**22%**) reported having faced this situation at least once. Table 5 presents the distribution of responses. ENT specialists reported having faced the situation the most often, followed by audiologists. However, these results do not reveal the origin of the recommendation to wear hearing aids.

Table 5 – The number of times, in the past five years, in which the respondents had observed a worker not using his/her hearing aids in a noisy workplace, despite a recommendation to do so (scenario 3)

Participants	Never	None over the past 5 years	1 to 10	11 to 20	21 to 30	More than 30	No response/ Refused to respond
ENT (29)	18		6	1	1	1	2
Occupational health (55)	43	1	8	1	1		1
Hearing aid dispenser (37)	27		4				6
Audiologist (77)	56		9	5	3		4

Question 19 (scenario 4): *Have you ever been faced with the following situation: a worker with hearing loss, of any nature, degree or origin* ***who does not use*** *his/her hearing aids,* ***but who can use*** *another electronic amplification device (FM system, hearing protectors with integrated communication system or another electronic protector)?* Almost a quarter of the respondents (**27%**) stated that they had been faced with this situation at least once. Table 6 shows the distribution of the frequencies reported. Proportionally, audiologists were the most numerous to report having faced this situation, followed by hearing aid dispensers.

Table 6 – The number of times, in the past five years, in which the respondents had observed a worker not using his/her hearing aids at work, but who could use another amplification device (scenario 4)

Participants	Never	None over the past 5 years	1 to 10	11 to 20	21 to 30	More than 30	No response/ Refused to respond
ENT (29)	19	0	6	1	0	0	3
Occupational health (55)	46	1	7	0	0	0	1
Hearing aid dispenser (37)	25	0	8	0	0	0	4
Audiologist (77)	46	2	22	2	2	0	3

At the very end of the questionnaire, the respondents were asked to comment. Between 22% (hearing aid dispensers) and 31% (audiologists) of the respondents did so. In their comments, the audiologists spoke of (1) the risk of aggravating hearing loss by using hearing aids in a noisy workplace (and, as a corollary, the actual technical capacity of hearing aids to limit exposure to levels that do not represent a danger to hearing); (2) other factors specific to the workplace, or to the worker, that could impede hearing aid function or use (dust, chemical substances, sweat, etc.); (3) the physical safety of workers; (4) the demands of the workplace and the tasks that require good hearing; (5) the adaptations that could be made to the workplace, the use of other assistive listening devices or electronic hearing protectors; (6) collaboration among the various health professionals; and (7) the importance for the worker to have all the information necessary to make an informed decision in this regard. Some audiologists say they would appreciate being informed of the study's findings and others call for clear evidence-based guidelines.

Hearing aid dispensers commented about (1) the means of ensuring detection of sound signals and maintaining communication abilities while protecting hearing (such as through various algorithms available in the hearing aids); (2) the interaction between hearing aids and hearing protectors; and (3) the importance of the worker having all the information necessary to make an informed decision about these matters. They said that they were also interested in being informed of the study's findings.

Attending physicians, both specialists (ENT) and general practitioners, had questions about (1) the risk of aggravation of hearing loss that hearing aid use in noisy workplaces could lead to; (2) the physical safety of workers; (3) the use of other assistive listening devices or hearing protectors; and (4) collaboration and divergences of opinion among various health professionals. Some attending physicians would like the study findings to be provided to various professionals, and especially to physicians.

The occupational health nurses and the physicians responsible for company workplace health programs commented about (1) the risk of aggravation of hearing loss that hearing aid use in noisy workplaces could cause; (2) workplace demands and tasks that require hearing; (3) the use of hearing protectors in general and those with systems to communicate or to listen to music in the workplace and, more generally, new technologies in the field; (4) collaboration among the various health professionals; and (5) other factors in the workplace that could cause problems to the operation or use of hearing aids (dust). Some of these professionals stated that they needed better information and clearer guidelines to give to workers.

3.3.3 Focus Groups

3.3.3.1 Focus Groups with Hearing Health Professionals

For each of the focus groups (audiologists, hearing aid dispensers, occupational health professionals), an analytical grid of the comments gathered was completed. The grid was made up of the following topics: (1) the origin of the request or the context of the worker's expression of need; (2) the workers' motivation to wear hearing aids; (3) the tools, protocols used, or the type of intervention; (4) the recommendations made to workers; (5) the obstacles; (6) the desired tools or resources; and (7) the feeling of professional efficacy.

An example of the grid containing an extract of the information gleaned from focus groups with audiologists is presented in Appendix B. What follows is a summary, by topic:

- The professionals recalled the contexts in which they met with hard-of-hearing workers. Unsurprisingly, these contexts vary depending on the occupation. While it is sometimes obvious that a worker exposed to noise would consult a professional because, for example, he or she got the results of a hearing screening performed at the factory, the situation is very different when a worker initiates a personal process to consult a hearing health professional. If the professional does not ask specific questions about the risk, the noise exposure could remain under-documented. It is also possible for a worker to have been treated for a long time by certain professionals because of a hearing loss diagnosed previously and that no one has thought of updating his or her file (change of job or workstation), and thus, of documenting the worker's exposure to noise.

- With respect to workers' motivation for using their hearing aids at work, as reported by professionals, the reasons cited are the following: effectiveness and autonomy at work, safety, communication with others and the desire not to be isolated from what is going on around them.

- With respect to actions, all of the professionals lament the lack of tools, protocols and resources. Most of them mentioned the paucity of information available about workstation demands and the noise levels or frequency spectrum of noise at one or more specific workstations. Furthermore, the measurement units for noise exposure are not always compatible with or transferable to those used to measure sound pressure on the eardrum. The professionals point to the absence of evidence about the risk of hearing aid use in noisy workplaces, in terms of noise characteristics and hearing loss, and on the genuine effectiveness of hearing aids in terms of the hearing abilities required at work. Discussions also revealed the existence of regional disparities. Thus, workers exposed to noise who consult for hearing problems will not necessarily receive the same information, the same advice or the same follow-up, depending on the avenue taken, the state of their hearing, the equipment and resources available, the experience of the professional consulted about occupational hearing loss and that of the rehabilitation counsellors and officers from the different regional offices of the CSST.

- The main recommendation to workers, on which all of the professionals consulted appear to agree, consists of not using hearing aids in noisy workplaces to protect their residual hearing. When noise levels are not as high, the directive about not wearing hearing aids is not as clear-cut. Many professionals would like to assess the actual danger and the potential benefits of hearing aid use on residual hearing in order to make an enlightened decision. The data on the subject remain incomplete. In the case of doubt, there is agreement about emphasizing workstation adaptation, while understanding that few workers can benefit from this process. Keeping hard-of-hearing workers working is also an issue for the professionals encountered.

- In addition to the lack of guidelines, clear protocols and uniform discourse, the various professionals admit that they do not consult with each other or work together very much, and that they have poor understanding of the scope of responsibilities of their colleagues. However, several among them were able to provide examples of where experience or collaboration had made a difference. The lack of human resources and training is also considered as an obstacle to the success of their actions.

- The professionals wanted to be more informed about new technologies, including the latest generation of hearing aids, active hearing protectors, communication systems and other products that could be looked at when workstations are adapted or to respond to the needs of a worker. They would like to have an inventory of these devices, the context for their use, the list of suppliers and their cost.

- The feeling of personal efficacy with respect to the use of amplification in noisy workplaces varies from one profession to another. Some professionals from the occupational health public health network report that they feel like they are “between a rock and a hard place,” given, for example, the mixed messages that workers may receive. Audiologists feel ill equipped to make informed decisions because there is no valid measurement protocol and little coordination, communication and cooperation among the various professionals involved in hearing health. Although they have more confidence in hearing aid technology, hearing aid dispensers note that a great deal of information, especially information about workplaces (e.g., noise level) and their demands (e.g. the hearing ability required to carry out the task) escapes them.

3.3.3.2 Focus Groups with Workers

An analytical grid also made it possible to analyze the comments received during the meetings with workers who used or did not use their hearing aids in noisy workplaces. The following topics were included in the analytical grid of the discussions carried out with the two groups: (1) the information requested by hearing health professionals; (2) instructions received about wearing hearing aids at work; (3) reasons for hearing aid use or non-use at work; (4) the benefits and drawbacks of wearing hearing aids; (5) safety concerns and (6) avenues for improvement.

An example containing extracts of information from the focus groups is presented in Appendix B. The following is a summary, by topic:

- Most of the workers affirmed that the hearing health professionals (in all the professions) did not ask many questions about their tasks at work and the demands of their workstations with respect to hearing, communication or localizing sound. Generally, the professionals asked them what kind of jobs they had and which company they worked for, without digging deeper. One worker mentioned that he was asked if he had problems hearing when he was on the telephone, but that he had not been told whether he should use the telephone at work.

- The directives given regarding hearing aid use in noisy workplaces varied from one worker to another. Some reported that they had received clear instructions not to wear them at work, whereas others had previously discussed the possibility of wearing them under earmuff-type hearing protection with their health professional. Others mentioned having asked the question and to have been told to decide on the benefits of wearing them themselves. Some did not remember whether the subject had been brought up during appointments with various professionals.

- The primary reasons given by workers for using their hearing aids at work were efficiency, autonomy, safety, the ability to hear different kinds of sounds (speech, alarms, noises indicating a malfunctioning machine, hearing someone approaching, etc.) and various abilities (detection, discrimination, localization, etc.). One worker wanted to be able to hear better during meetings, another felt incapacitated when he didn’t have his hearing aids, and another used them mainly to mask troublesome tinnitus.

- The benefits reported were not directly related to work (listening to music, watching television at a lower volume, etc.), but could have an indirect impact on their occupational activities. For example in the case of the worker with tinnitus, being able to mask that abnormal sensation helped him do his job better; in the case of the worker who felt incapacitated without his hearing aids, wearing them could have an influence on his feelings about work. Those who did not wear their hearing aids at work mentioned that the level of ambient noise made it impossible for them to use them. Some tried using them but were unable to tolerate them. Those workers were also concerned with eventual damage to their hearing caused by hearing aid use.

- All the workers encountered were concerned about safety. They were conscious of the dangers related to not hearing, both for themselves, as they are hard of hearing, and for those with good hearing, but who cannot hear something because of noise. They reported having to be doubly vigilant.

– Because of their hearing difficulties both at work and in their personal lives, these hard-of-hearing workers constitute a group with a measure of hindsight about the various steps or events that led them to getting hearing aids. When asked the question “With what you know now about hearing loss and hearing aids, how could the process be improved?” Some workers spontaneously mentioned using non-hearing strategies to enable detection and communication (e.g., a visual signal to replace a sound signal, moving the telephone into a quieter environment). They also asked questions for which they would now like responses: “do all hearing aids work in the same way?,” “is it dangerous to use them under earmuffs?,” “does the FM system that was suggested for me to use at home also work when I’m on the job?” A worker remembered that the only message he remembered after repeated auditory screenings performed at the factory is that he had to wait, that his hearing was better than the compensation threshold in the CSST’s *Scale of Bodily Injuries*. He now wonders if he should have acted instead of waiting to become eligible for compensation from the CSST because of occupational hearing loss. Others wondered if there wasn’t a way of making adjustments to hearing aids in the workplace, under actual noise conditions. They even suggested being able to use a device that would enable them to adjust their hearing aids at their own convenience, and to remember the parameters and report them afterwards to their hearing aid dispenser. The workers also wanted to better understand the range of use and the limits of their hearing aids.

3.4 Discussion

The implementation of phase 1 of the study showed us that the issue of hearing aid use in noisy working environments has not caught the attention of the scientific community, as demonstrated in the results of the literature search of documents published up to 2012. We were unable to document how often the issue occurs.

However, the consultation with health professionals made it possible to establish that this is a relatively frequent situation in Québec. In fact, almost everyone consulted reported that they had observed, at least once over the last five years, someone wondering about the possibility of using his or her hearing aids at work or someone who was using them in a noisy work environment.

These meetings with health professionals and workers who use or do not use hearing aids demonstrated an often isolated search for solutions that fails to reconcile all of the needs reported by these workers. There is an attempt to protect the residual hearing of workers by discouraging hearing aid use in very noisy workplaces, but, in some cases, in doing so, these workers’ need to hear for reasons of efficiency, safety and communication is underestimated. In less noisy environments, the viewpoints about the actual danger of over-amplification, related to the use of hearing aids, varies, as do the recommendations made to workers about wearing their hearing aids.

The professionals deplore the absence of valid methods to measure the risk of over-amplification associated with wearing hearing aids in noisy work environments and clear protocols to adjust and evaluate their effectiveness according to workers' hearing, communication and sound localization needs. Moreover, they all recognize that they do not have all the information required to completely document all of the sound contexts and hearing demands of the workstations of the workers concerned and for whom these decisions must be made. The extent of their professional responsibilities is not well known and could also be better defined.

4. RISK OF AGGRAVATING HEARING LOSS (PHASE 2)

4.1 Objective

The second phase aims to examine the risk of aggravating hearing loss in workers by the use of hearing aids in noisy workplaces. It also has the objective of establishing valid measurement methods to assess the risk of aggravating hearing loss in the workers concerned.

4.2 Methodology

A review of the scientific literature on the risk of aggravating hearing loss from wearing hearing aids, using various databases (Scopus, CINAHL, Pubmed, Medline, Google Scholar, Web of Science and Google), made it possible to identify, for the period between 1957 to 2014, 84 documents deemed to be relevant and available in French or in English. The keyword “hearing aid” was combined with each of the following terms during the bibliographic search: “hearing deterioration” and “loss” and “aggravation” and “worsening” and “damage”; “auditory fatigue”; “threshold shift”; “permanent threshold shift”; “temporary threshold shift”; “noise exposure”; “over-amplification” and “excessive amplification”; “work” and “workplace” and “occupation” and “occupational” and “worker”; “occupational” and “workplace noise”; “otoacoustic emissions.” An examination of the “Methodology” section in the articles listed enabled the risk of aggravation measurement methods used to be identified and their validity assessed.

4.3 Findings

The following pages summarize the state of knowledge on the risk of aggravating hearing loss by hearing aid use and on the methods used to assess that risk, in addition to listing some of the recommendations suggested in the literature for hearing aid use in noisy workplaces. A more detailed description of this data is provided in Appendix C. Because of a dearth of articles that focus specifically on workers in noisy workplaces, the search was broadened to include the risk of aggravation among all hearing aid users.

4.3.1 Evidence of the Risk of Aggravating Hearing Loss by Hearing Aid Use

Notable deterioration of residual hearing due to hearing aid use is not unanimously recognized in the scientific articles. Although several authors report significantly higher deterioration in auditory thresholds over time in those who use hearing aids compared to those who do not, findings from other studies do not support this observation, or are less conclusive.

It is also difficult to draw clear and generalizable conclusions about the issue in question because the group under study in most of the articles listed (i.e., children with significant hearing loss and fitted with monaural linear analogue hearing aids) appears to be different in several respects than workers in noisy workplaces (for example, in terms of degree of hearing loss, level of sound exposure, binaural devices with more advanced technology).

4.3.2 Methods to Evaluate the Risk of Aggravating Hearing Loss by Hearing Aid Use

4.3.2.1 Methods to Evaluate the Risks Applicable to Groups

The most frequently used risk-evaluation method to quantify the risk of aggravating hearing loss in groups of individuals is audiometric monitoring. Despite its simplicity, it has several shortcomings. We first note that an analysis based on group data may easily obscure substantial individual differences, much in the same way that the average thresholds on a range of frequencies do not make it possible to highlight a deterioration in specific frequencies that are potentially more sensitive to noise exposure. The absence of a pre-amplification hearing assessment and the unspecified interval between the hearing aid fitting and the last audiogram are also occasionally noted methodological shortcomings. Moreover, other major factors that could have a significant effect, such as the maximum output of the hearing aid, its gain, adjustment of its volume, the presence of a noise reduction algorithm (and other parameters), the duration and frequency of use, and the nature and initial degree of hearing loss, are little documented or monitored in group studies.

Despite such limits, some authors have demonstrated a positive correlation between the degree of deterioration of hearing in the ear fitted with a hearing aid and the maximum output and/or gain of the hearing aid, as well as the volume used, and a negative correlation with hearing thresholds at the time of fitting (an initial hearing loss that is more pronounced being associated with less significant deterioration).

4.3.2.2 Methods to Evaluate the Risks Applicable to Individuals

On the individual level, several evaluation methods applicable to the aggravation risk of those using hearing aids were identified in the literature, i.e., (1) individual audiometric monitoring (permanent threshold shift, temporary threshold shift and otoacoustic emission measurement); (2) the estimation of noise exposure levels ($L_{ex,\ 8h}$) by dosimetry, by measurements with a coupler or an acoustic manikin and by etymotic measurements and (3) predictive models.

4.3.2.2.1 Individual Audiometric Monitoring

The auditory thresholds measured at various points in time can be compared to determine whether a drop in hearing in the ear fitted with a hearing aid can be attributed, at least in part, to over-amplification. However, this approach appears to have a number of weaknesses. For example, because of a measurement error, some irreversible hearing damage could occur even before a significant difference appears when the hearing thresholds are measured. Moreover, because bilateral hearing aids are preferred these days, the ear not fitted with a hearing aid can no longer serve as a control to separate the effect of amplification on hearing from other factors. Finally, using repetitive audiometric measurements over time to determine the risk of over-amplification requires very rigorous control of a number of parameters (e.g., compliance with standards in place, preparing the individual for the evaluation, the acoustic conditions during the examination, etc.).

The measurement of temporary threshold shifts can make it possible to establish a causal link between the deterioration of thresholds and hearing aid use, especially when recovery of thresholds is noted after a period of them not being used. This method can also be useful in terms of bilateral fitting, because the comparison rests on the hearing measured before and after short periods of hearing aid use, instead of hearing in the fitted ear being compared to the ear not fitted with a hearing aid. There could be difficulties in using this type of approach in noisy workplaces, however, in addition to some of the other factors previously enumerated. For example, it could be difficult, or even impossible, to measure thresholds at specific times, while ensuring adequate and reproducible measurement conditions, especially since pre-exposure measurements (before the work shift) must be performed.

The disappearance or modification of otoacoustic emissions can also signal the appearance of hearing damage. The presence of these emissions depends on the integrity of the external hair cells, and they are generally reduced or absent in cochlear hearing loss above 40-60 dB HL. The use of otoacoustic emissions is, however, limited to individuals who have normal hearing or slight to moderate sensorineural hearing loss, which probably excludes workers who must or who choose to wear hearing aids in noisy workplaces. Their potential for use in monitoring individuals at risk is also reduced because the correlation between threshold shifts and otoacoustic emission changes following noise exposure is not clearly established. These limits mean that measuring otoacoustic emissions is not the best way to quantify the risk of over-amplification among workers who wear hearing aids at work.

4.3.2.2.2 Estimation of Noise Exposure Levels (Lex, 8h) by Dosimetry, by Measurements with an Acoustic Coupler or Manikin and by Etymotic Measurements

The methods typically used to estimate exposure to noise in noisy workplaces, using a sound level meter or a dosimeter, do not directly apply to situations in which the worker wears a hearing aid or any other device covering the ear and blocking the ear canal. In such cases, the sound pressure in the ear, behind the device, must be measured or estimated and then converted to a free or diffuse field equivalent to the position of the absent worker in order to compare it to regulatory limits. This approach makes it possible to evaluate the risk of aggravating hearing loss, and for all other sources of noise that are a distance from workers.

The methods to measure sound levels in the situation of an occluded ear most directly applicable to the issue of hearing aids are the use of a microphone in the ear of an acoustic manikin or in an artificial ear. By extension, HA-1 and HA-2-type couplers, often used in analyzing hearing aids, could also be considered. In each case, the exposure levels must be corrected to obtain their equivalent in the sound field, expressed in dBA. These different methods presume that the level of sound pressure on the eardrum is directly related to the risk of hearing damage, that the source is situated in a sound field at a distance from the worker (e.g., machine) or placed in the ear (e.g., earphone).

In all these approaches, one-third octave measurements are carried out throughout the duration of the exposure, transformed into SPL decibels in the sound field and finally converted into dBA. It is assumed that a level of sound pressure measured against the eardrum in an occluded ear canal and transformed into its equivalent sound field is as dangerous as an identical sound level measured directly in the sound field. Some studies cast doubt on this hypothesis and appear to indicate that the measure of sound pressure levels on the eardrum, in the presence of a sound source in the ear canal would result in an overestimation of noise exposure. In the case of hearing aids worn by workers, such an approach would therefore be more conservative, as it would overestimate the genuine noise exposure level.

4.3.2.2.3 Predictive Models

To assess the risk of aggravating hearing loss among hearing aid users, some authors have used mathematical models to predict either the sound exposure levels or the deterioration of auditory thresholds.

A quantitative model based on the octave band method used to predict the sound level behind hearing protectors was used to predict the hearing aid gain levels that are considered safe, taking into consideration the sound exposure levels and attenuation provided by the hearing protector (if applicable). The quantitative model enables predictions to be made for each frequency between 125 and 8000 Hz, on the basis of noise levels (dB SPL), of the attenuation of the concha and the gain of the hearing aid measured or calculated according to the revised method of the National Acoustic Laboratories (NAL-R). Correction factors for the microphone frequency response and the resonance of the concha are also taken into consideration. The attenuation values of the protectors are first subtracted from the noise levels to which the worker is exposed. The outcome of this step translates into the sound pressure levels behind the protector without the influence of the hearing aid. The measured or calculated gain values are then added to the levels to obtain the sound levels with the hearing aid worn under the hearing protector. Those values are then corrected to take into account (1) the differences between the probe-type microphone used during measurement of gains and that used in the sound field and (2) the effects of resonance on the concha. Using a model, the maximum gain levels of the hearing aid that are considered safe can also be calculated by subtracting the sound pressure levels with the hearing aid behind the hearing protectors from the maximum sound exposure permitted.

The estimation of sound exposure levels is an interesting approach for studying the risk of over-amplification. It appears, however, that the utility of such an approach is limited by two interrelated factors, i.e., (1) the need to transform the values measured at the eardrum with the hearing aid activated into an equivalent sound field, and (2) the fact that the risk criteria commonly used are typically based on the effect of sound exposure on individuals with normal hearing. Additional corrections would probably be necessary in cases of hearing loss.

Some authors have instead used mathematical models to predict the magnitude of temporary or permanent threshold shifts associated with the use of hearing aids. Generally, these models also take into consideration the combined effect of age and noise exposure to predict the quantity of threshold shifts (temporary or permanent) expected among adults with normal hearing, by then correcting for people with sensorineural hearing loss. However, in this type of approach, the equivalent level of continuous sound exposure while hearing aids are being used must first be established. The validity of predictive methods appears, however, to be limited to linear hearing aids, because the levels of amplified exposure are generally established on the basis of hearing aid gain values. It is important to note that most hearing aids currently available on the market and prescribed are no longer of the linear type.

4.3.3 Recommendations Concerning Hearing Aid Use in Noisy Workplaces and the Risk of Aggravating Hearing Loss

Recommendations for workers who wish to or who should wear hearing aids in the workplace are not clearly established and are rather rudimentary. In general, professionals recommend that hearing aids should never be worn in noisy environments characterized by noise levels above 90 dBA (instead, hearing protectors should be worn) and that workers who wear hearing aids must be clinically monitored, even if the sound levels in the workplace do not exceed the established criteria for action.

While hearing aids can generate sound levels that can damage hearing, even if they are equipped with circuits that limit loud sounds, some believe that a personalized adjustment, according to established prescriptive methods, is safe in most cases. To limit the risk of aggravating hearing loss, the recommendations are to (1) adjust the hearing aids according to the established prescriptive formulas; (2) ensure that the values at the eardrum are lower than the maximum values suggested by regulatory organizations; (3) determine the input level necessary to produce such values and (4) estimate the genuine amplification levels based on daily activities, their duration and their frequency.

When there is a risk of over-amplification, diverse technical solutions (dynamic range compression, multiple memory hearing aids, directional microphones, noise reduction algorithms, FM system, volume controls, use under an earmuff-type hearing protector, use of a communication helmet instead of hearing aids, etc.), binaural amplification to reduce the gain required in each hearing aid, and environmental options, such as temporarily not wearing hearing aids are recommended.

Finally, appropriate adjustment and verification of hearing aids cannot guarantee that hearing will not deteriorate. Regular clinical monitoring of workers who use one form or another of amplification in noisy workplaces could make it possible to determine hearing deterioration early on, while taking into account the limits associated with such an approach (such as errors in the audiometric measurements).

4.4 Discussion

On the basis of a review of the literature, presented in Appendix C, it cannot be clearly concluded that there is a risk of aggravating hearing loss through hearing aid use. In fact, most studies on the subject date back several years and are based on obsolete technologies, or do not specifically deal with the issue of working in noisy workplaces.

In addition, despite the diversity of methodologies proposed in the various articles identified (i.e., audiometric monitoring, estimation of noise exposure levels and predictive models), none of these methods appear valid and reliable enough to estimate or precisely predict the risk of aggravating hearing loss when hearing aids are worn. Faced with a lack of standardized tools and methods, professionals appear to prefer measuring sound levels at the eardrum, which are then transformed into their equivalent free field and compared to permissible sound levels determined by the various jurisdictions. The value of 85 dBA for eight hours of exposure is often cited in the literature as the permissible exposure limit, even if the World Health Organization sets 75 dBA for an eight-hour period as the guideline value to limit all hearing threshold shifts.

Finally, recommendations for workers who wish to or who should wear hearing aids in the workplace are not clearly established and remain quite limited. With respect to research, a review of alternative or additional options to hearing aid use appears necessary, as is the establishment of clear protocols for hearing health professionals to adequately manage this issue.

5. THE EFFECT OF AUDITORY AMPLIFICATION ON SPEECH PERCEPTION IN NOISY CONDITIONS AND ON SOUND LOCALIZATION (PHASE 3)

5.1 Objective

The objective of the third phase was to document the effectiveness of hearing aids in supporting the hearing capacities necessary to autonomously and safely carry out tasks in the workplace, i.e., speech perception in a noisy environment and sound localization. More specifically, the effects of noise reducers and directional microphones on speech perception and the effects of various technologies on sound localization were explored.

5.2 Methodology

A review of the literature was carried out by consulting databases (Medline, Scopus, CINAHL, PubMed, IEEE Xplore Digital Library, Google Scholar). From these databases, 57 references specialized in audiology or occupational health and safety, dating from 1998 to 2012, were obtained. Table 7 presents the keywords that were used to do the search. Moreover, additional relevant articles were identified from the reference lists of the articles retained.

Table 7 – List of key words for each of the topics discussed in phase 3

Noise reducers and speech perception	Directional microphones and speech perception	Diverse technology and sound localization
hearing aid, noise, speech perception, noisy environment, noise reduction	hearing aid, noise, speech perception, noisy environments, workplace, directional microphone, industry	hearing aid, localization, CIC, noise, sound localization, hearing loss, amplification, directional microphone, noise reduction

5.3 Findings

The following sections succinctly summarize the state of knowledge. Exhaustive descriptive tables[4] were prepared for each of the themes in Table 7. The studies identified in the literature dealt with sound environments that were often not very representative of the acoustic conditions in workplaces (with respect to level, frequency content, reverberation duration, etc.), which added limits to the interpretation of the findings and their generalization to the targeted population, workers exposed to noise.

[4] These tables can be transmitted if necessary by contacting the first author of the study at tony.leroux@umontreal.ca.

5.3.1 Effect of Noise Reducers on Speech Perception

Although different methodologies were used in the studies, significant improvement in speech perception associated with noise reducer use was reported in only 4 of the 18 articles retained; the others did not indicate any significant improvement or deterioration related to the technology. Although noise reducers do not seem to be as advantageous as directional microphones in improving performance in speech perception trials, their use is recommended because of the numerous subjective benefits reported by users, in terms of improvement in hearing comfort, listening effort and sound quality. In addition, noise reducers can help reduce levels of sound exposure, at least when compared with the same hearing aid model used without noise reducers. However, it is important, during the intervention process, to instil realistic expectations in users about the positive effects of noise reducers, despite the paucity of information available to health professionals about the algorithms used in the hearing aids of various manufacturers.

5.3.2 Effect of Directional Microphones on Speech Perception

There was significant variability in the sample of 21 articles analyzed, not only in the documented advantages of a directional microphone for speech recognition in noisy environments compared to performance in omnidirectional mode, but also in the methodology used. In general, the advantage of a directional compared to an omnidirectional microphone on the speech reception thresholds for sentences in noise can reach 15 dB, but most of the articles report an average advantage in the range of 2 to 5 dB. It appears that this advantage depends greatly on the methodology used to quantify it and also on the type of noise, the number of noise sources, the location of noise sources in relation to that of speech, the number of microphones in each hearing aid, the type of directivity pattern and its operational mode (cardioid/hyper-cardioid, adaptive/fixed) and the type of earmold used (closed/open fit). There is an additional advantage of approximately 2 dB for the adaptive directional microphone compared to the fixed directional microphone, except in the presence of diffuse noise, where the performances are similar. In addition, the use of an open fit earmold appears to reduce the advantage provided by a directional microphone compared to the use of a closed fit earmold.

Finally, with respect to the subjective evaluation of directional microphones compared to omnidirectional microphones, it appears that a third of the users experience no difference among the different types used (omnidirectional or directional, adaptive or fixed). One third used the omnidirectional mode more often and one third preferred the directional mode. The users preferred the directional microphone when they were faced with varied sound situations or when they were in the presence of noise, while the omnidirectional mode was preferred for localizing sound.

5.4 Effect of Diverse Technologies on Sound Localization

With respect to sound localization ability, the 18 articles identified and analyzed explored different conditions of hearing aid use, including aided performance compared to unaided performance, unilateral amplification compared to bilateral, microphone position, microphone directivity pattern, various signal treatment strategies (such as noise reducers, binaural communication, the preservation of the intra-aural phase, the impact of open fit earmolds compared to closed fit earmolds, frequency compression and various combinations of these signal treatment strategies) and the acclimatization period.

In general, sound location performances are better without hearing aids than with them, especially in terms of front/back confusion. Bilateral amplification is usually better than unilateral amplification in supporting this hearing task.

The effect of microphone positioning remains somewhat inconclusive, because the results of various studies are contradictory. While some studies give more of an advantage to CIC-type devices over the BTE type with respect to front/back confusion, other studies appear to suggest that the position of microphones has only a small impact on sound localization. Contrary to the widely held belief among hearing health professionals, directional microphones could improve sound localization compared to omnidirectional microphones, especially in situations of front/back confusion. The directivity pattern and sound signals used seems to be, at least in part, responsible for this improvement.

The various signal treatment strategies can also have an impact on hearing localization, by changing the indicators required for that task. For example, some studies have shown that dynamic range compression operates differently in each ear, which could negatively affect spatial perception, as sounds are perceived as being diffuse and in movement. While certain studies have shown that sound localization can be maintained even with an active noise reducer, other studies report deterioration in this hearing task. It is difficult to draw clear conclusions about the effect of various parameters of hearing aids on sound localization given the small number of studies focused specifically on one parameter, the complex interaction among the various parameters and the wide range of methodologies used to study their effects.

Ultimately, after the adjustment of hearing aids, sound localization performance, depending on various signal treatment strategies, can change after an acclimatization period during which the user becomes accustomed to the hearing aids and is able to achieve the greatest benefit from them. This period may take several months depending on the age of the user and his or her cognitive functions.

5.5 Discussion

Hearing aid use can either help improve or worsen the hearing abilities necessary for autonomous and safe execution of tasks in the workplace. Hearing aids can sometimes reduce speech perception, especially when used in omnidirectional mode. Directional microphones appear to improve this capacity, with an average directional advantage (compared to omnidirectional) of approximately 2 to 5 dB, reported in most studies; this advantage is, however, limited when wearing open fit earmolds compared to closed fit earmolds. Adaptive directional microphones offer an additional approximately 2 dB advantage compared to fixed directional microphones in non-diffuse noise conditions, in which speech and noise are spatially separated.

Unlike directional microphones, there is little evidence that noise reducers are beneficial for speech perception in a noisy environment. However, with respect to hearing comfort, listening effort and sound quality, the subjective impression seems favourable. Noise reducers can also help decrease sound exposure levels, but there do not seem to be methods or standardized evaluation protocols to measure residual sound exposure level.

With respect to the effect that hearing aids have on sound localization ability, results are less conclusive in terms of worker safety. In general, sound localization is better without hearing aids than with them, especially in the front/back dimension compared to the left/right dimension, which appears to be less affected. In fact, several hearing aid adjustments can change the indicators necessary for sound localization. While it is difficult to draw clear conclusions, because of the wide range of parameters to study and the methodologies used in various studies, it appears that directional microphones have the potential to improve front/back localization ability compared to omnidirectional microphones. An acclimatization period could also be beneficial, but may not be practical. However, not having time to acclimatize to a directional system could compromise the safety of hard-of-hearing workers in noisy environments.

To summarize, the findings of the studies identified in the literature are, for the most part, difficult to generalize to the population targeted in this study. The stimuli, the environments, the organization, the hearing and communication demands in the workplace, as well as individual hearing characteristics, may be very different than the methodological contexts identified in these studies.

6. NEW AMPLIFICATION AND PROTECTION TECHNOLOGIES (PHASE 4)

It must be remembered that in noisy environments, many workers with hearing loss are faced with a challenge that very often pits their communication needs against their hearing and physical protection needs. To accomplish their tasks efficiently, while ensuring their safety and that of others, these workers must be able to hear important signals such as speech or warning signals, despite the attenuation provided by protectors. In order to meet their communication and hearing protection needs, workers can opt to use hearing aids (either on or off), wearing hearing aids under earmuffs or using conventional passive or active (electronic) hearing protectors. Some of these options were dealt with in phases two and three of this report. Phase four deals more specifically with active hearing protectors. Sound restoration devices, hearing protectors with integrated communication systems and active noise reduction (ANR) protectors are active hearing protectors.

The market has witnessed a rapid increase in the use of these products the industrial, military and police sectors (Casali, 2010a; Giguère et al., 2011a), and are an option to consider in order to reach the double objective of adequate hearing protection and maintaining consciousness of one's sound environment, especially for people with hearing loss (Dolan and O'Loughlin, 2005; Giguère et al., 2011b). Compared to passive protectors, they provide some flexibility in terms of adjustment according to the hearing conditions in which they are used. However, there is no detailed method to select a product, or standardized guidelines to guide their adjustment to ensure protection and adequate awareness of the surroundings. Some products have integrated radio functions that enable long-distance communication. Current research is focusing on the effect of active hearing protectors on the perception of warning signals, sound localization and perception of speech close by and far away (e.g., Abel et al., 2007, 2009, 2011, 2012; Casali et al., 2007; 2009; Nakashima and Abel, 2009; Alali and Casali, 2011, 2012; Giguère et al., 2011b, 2012a; Casto and Casali, 2012).

6.1 Objective

The objective of the fourth phase was to review the state of knowledge of the new active hearing protector technologies and, in particular, sound restoration devices, that can facilitate listening, communication and localization, while limiting exposure to noise.

6.2 Methodology

A review of the literature on active hearing protectors and their effects on various hearing abilities was completed using a collection of articles amassed by the researchers during previous projects. An Internet search was also carried out. Several keywords were used in the Google search engine, including "level dependent hearing protector"; "hearing protection for people with hearing loss"; "intelligent hearing protection" and "dynamic hearing protection for people with hearing loss," to identify the lesser-known manufacturers of sound restoration devices. Consultation of the Internet sites of various manufacturers or their representatives, as well as discussions during meetings of the technical standardization committees with members of CSA, ANSI and ISO were also useful.

6.3 Findings

6.3.1 Description of Active Hearing Protectors

In sound environments and more complex work situations, active protectors should protect hearing against harmful continuous and impulsive noises, while enabling awareness of the sound environment (e.g., perception of sound alarm signals, sound localization, verbal communication and detection of sound signals from a distance), both in the immediate environment and during radio communications. The paragraphs below, based on reviews of the literature carried out by Brammer et al. (2008) and Casali (2010b), dealt with recent developments and current issues in the field of active hearing protectors and cutting-edge communication systems.

Rapid technological progress in the field of electronics and digital signal processing over the past years has brought with it renewed interest in hearing protectors equipped with microphones, headphones and other electronic components. In general, these devices have one or more of the following objectives: (1) providing more significant attenuation than the characteristic passive attenuation of the device, through the use of an active noise-reduction algorithm or phase cancellation technology; (2) raising awareness of the sound environment through variable attenuation in accordance with the sound levels present in the environment and (3) incorporating radio communication functions to enable long-distance communication. The second objective, which is directly related to the targeted issue, is discussed more fully in the following paragraphs.

Sound restoration devices, which are represented schematically in Figure 4, are specifically designed to amplify sounds reaching the ear to a value that depends on the sound level present in the environment. They have several electroacoustic components, including microphones (E and R) and a headphone (S). In some models, when the sound level of microphone E does not exceed the limit established by standards for noise exposure in the workplace, the sounds of microphone R are amplified and then sent to headphone S to improve their audibility. This signal processing method may require analogue or digital circuits. In the simplest systems, speech and environmental noises are amplified, usually preferentially for frequencies corresponding to speech sounds (e.g., frequencies above 125 Hz).

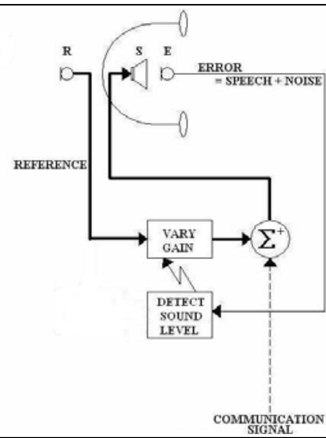

Figure 4 – Schematic representation of a sound restoration hearing protector (from Giguère et al., 2011a)

As illustrated in Figure 4, a detector continually monitors the sound level under the earmuff (in E). When the sound level exceeds a predetermined value, the gain between S and E is immediately reduced. In simpler systems, the gain stays constant and the device acts as a linear amplifier when the sound level under the earmuff is below the upper level that had been set. Other systems have automatic gain control (AGC) to ensure a more gradual reduction in gain. More sophisticated systems use complex algorithms to preferentially amplify the speech of someone speaking face-to-face with the user. It is important to note that in Figure 4, gain setting is not only under the direct control of the detector, but the user can also manually vary the basic gain using volume controls, typically in a range of 12 to 18 dB (but sometimes more), or by turning off the amplifier for passive attenuation only. According to the placement of the volume control in the AGC circuit, output compression (*AGCo*) or input compression (*AGCi*) are possible; these are compressive functions that resemble those found in hearing aids. An example of a product that operates according to each compression mode is presented in the following section.

6.3.2 Examples of Output Compression (AGCo) and Input Compression (AGCi) Products

The Threat4 X-62000 is a hearing protector of the in-earplug type with an integrated communication system specifically designed for military applications. It comes with functions that enable talk-through communication using the sound restoration principle, with five gain settings, varying from 0 to +12 dB, in addition to “off” mode, and radio communication (the volume must then be adjusted on the external radio unit). The Threat4 X-62000 is compatible with a wide range of commercial and military radios, and it is generally used with Comply™ foam earplugs (Oakdale, Minnesota). The certified attenuation of foam earplugs inserted in the auditory canal correspond to an A-weighted noise reduction value (Noise Reduction Statistics for A-weighting (NRSA) of 32-39 dB (ANSI/ASA S12.68-2007 R2012).

The estimations of gain at various volume settings in oral communication mode can be obtained using objective measurements performed with a standardized manikin (ANSI S3.36-1985 R2006). Figure 5 illustrates the sound levels in the manikin’s ear according to free field sound levels for the five gain settings available in the oral communication mode of the Threat4 X-62000, in addition to a non-occluded ear condition. We note an increase in sound levels in the manikin’s ear (output) if we increase the sound level of the stimuli (input), at all gain settings, to the maximum level of 87dBA in the manikin’s ear. The form of the input/output waves clearly indicate that the Threat4 X-62000 oral communication system the acts like an AGCo circuit in a hearing aid (Dillon, 2001; Volanthen and Arndt, 2007) with a very high compression ratio. As expected, the manikin levels are higher at the higher gain settings for sound stimuli at a low to moderate level (<70dBA). In general, the limit of the system’s output is adjusted at a level of approximately 87 dBA in the ear, which corresponds to an equivalent free field of approximately 80 dBA.

Figure 5 also illustrates the insertion gain of the Threat4 X-62000 for octave bands between 125 and 8000 Hz in response to pink noise at 60 dBA, the level at which the device acts like a linear system. The maximum gain is situated at 2000 Hz. The curves representing the various gain adjustments in the oral communication mode are essentially parallel, which indicates that the increase in gain from one setting to the other is equal to all the frequencies in the 125 to 8000 Hz range.

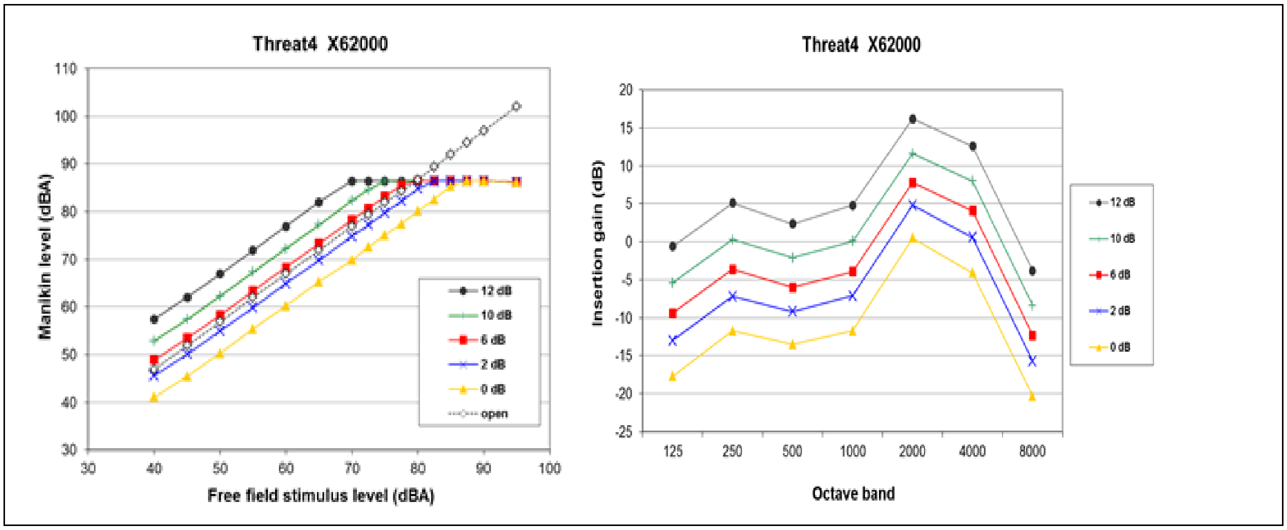

Figure 5 – Threat4 X-62000: input/output curves in a noise spectrum of speech (left) and insertion gain according to the frequency in response to pink noise of 60 dBA (right)

The PELTOR PowerCom Plus is an earmuff-type device with a boom microphone, which provides oral communication capabilities (five gain settings available from 1 to 5, and an “off” button) to enhance awareness of the sound environment at low to moderate noise levels, while protecting hearing at high noise levels. The device thus provides hearing protection that varies, depending on the sound level (passive attenuation only) with a noise reduction rating (NRR) of 25 dB. According to the manufacturer’s information, average passive attenuation varies from 19 to 39 dB at 125 to 8000 Hz.

Figure 6 illustrates the sound levels at the manikin’s ear according to free field sound levels for the five gain settings (1 to 5) of the PELTOR PowerCom Plus and the non-occluded ear condition. There is a linear increase (level of 1.0 dB/dB) of sound levels in the manikin’s ear (output) with an increase of the sound level of stimuli (input), at each of the gain settings, up to an approximately 60dBA input level (the compression threshold). Afterward, the device compresses the signal (increase in the output level is less than that of the input level), with a compression ratio of approximately 4:1, meaning that the output level increases by 1 dB for each 4 dB increase of input level. As expected, for a given level of stimulus, the manikin levels are higher for higher gain settings, and the gain curves are all parallel. These characteristics indicate that the PELTOR PowerCom Plus acts like the AGCi circuit of a hearing aid (Dillon, 2001; Volanthen and Arndt, 2007). Therefore, the output limit of the PELTOR PowerCom Plus depends on the gain setting (Figure 4), unlike the Threat4 X-62000 (Figure 5), which operates according to the AGCo principle.

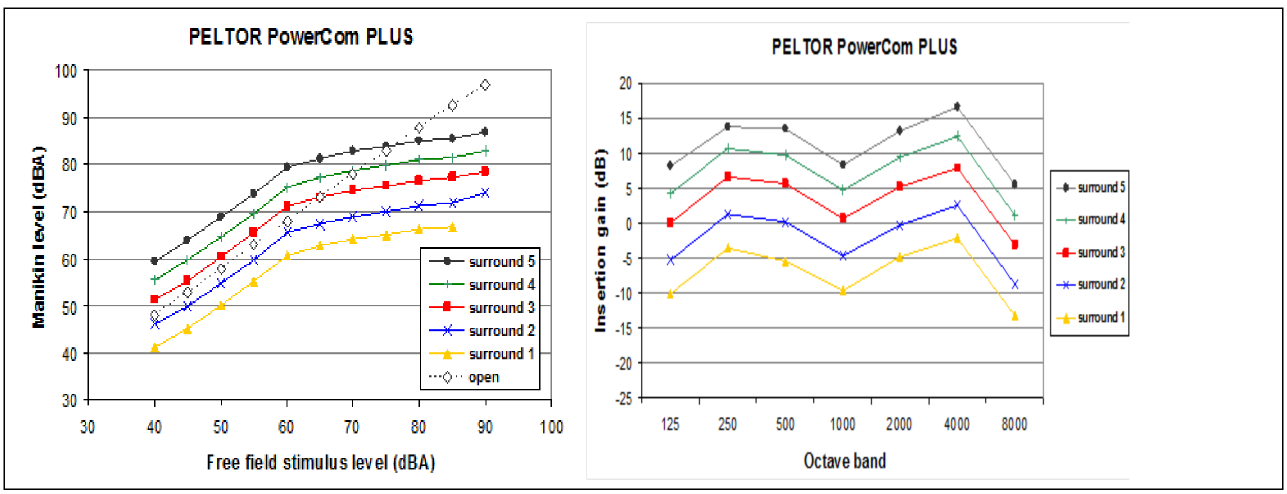

Figure 6 – PELTOR PowerCom Plus: input/output curves in a noise spectrum of speech (left) and insertion gain according frequency function in response to pink noise of 60 dBA (right)

Figure 6 also shows the insertion gain of the PELTOR PowerCom Plus for octave bands of between 125 and 8000 Hz in response to a noise spectrum of speech at 60 dBA. Like the Threat4 X-62000, the increase in gain setting is essentially uniform over all frequencies. The maximum gain is situated at 4000 Hz and there is a trough of approximately 5 dB at 1000 Hz. The insertion gain of the device, averaged over the four frequency bands between 500 and 4000 Hz, is of -5.6,

-0.6, 4.8, 9.0 and 12.9 dB for stereo settings 1 to 5, respectively. Although the manufacturers' comparative data are not available, the technical data sheet indicates that the hearing aid amplifies up to 18 dB. This value is similar to the difference in gain measured between the gain settings from 1 to 5 (18.5 dB).

6.3.3 Review of Recent Studies about Active Hearing Protectors

Relatively few independent studies have been carried out in the field or the laboratory to assess the advantages and limits (in terms of hearing tasks and the operational performance) of active protectors compared to passive protectors, or in situations where hearing is not protected (non-occluded ear). The following paragraphs discuss some recent studies that deal with sound detection, sound localization and speech perception.

6.3.3.1 Sound Detection

As expected, sound detection in silence is generally better with sound restoration devices than with conventional passive protectors, because of their weaker attenuation at low input levels. Among individuals with hearing loss, when active protectors are used at high gain settings, an improvement in hearing thresholds can be noted compared to a non-occluded ear. However, for people with normal hearing, this advantage is somewhat limited by the audible buzzing generated by the electronic components of the device (Abel and Giguère, 1997). Compared to the potential benefit of variable attenuation on hearing levels, an active noise reduction hearing aid without sound restoration can have the consequence of increasing detection thresholds in silence compared to the same device used in passive mode (Nakashima, 2007; Abel and Spencer, 1997).

Casali et al. (2009) demonstrated that, at least for an active earplug with an integrated communication system characterized by a 36 dB gain in oral communication mode, the detection distance could be improved by 80% compared to unprotected hearing, which demonstrates the potential advantages, in silence, of sound restoration protection systems in operational environments. In another study that examined several passive and active protectors, Alali and Casali (2012) demonstrated that the detection distance could be lessened when conventional passive protectors were used, compared to unprotected hearing, while it remained comparatively unchanged with sound restoration devices, at least for relatively low noise levels (52 dBA).

While sound restoration devices have a notable advantage in silence and for low noise levels, studies have demonstrated that a sound restoration earmuff is no better than a passive protector in detecting backup alarms by people with normal hearing in noises of between 75 and 95 dBA (Abel et al., 1991, 1993; Casali and Wright, 1995).

Similar results were reported by Giguère et al. (2012a) during a multidimensional assessment of the performance of a sound restoration earmuff. The detection thresholds of two types of backup alarm (pure tone alarm and broadband alarm) were measured at various incidence angles in silence and in a factory emitting noise of 86 dBA. In silence, the detection thresholds were significantly higher (poorer) for the device in "off" mode compared to the situation without protection, which is as expected, given the passive attenuation provided by the device. In oral communication mode, with approximately 2 dB of gain in low sound, the detection thresholds were similar to those of the condition without protection, showing the advantage of amplification at low sound levels. However, in noise, the thresholds were similar in every listening condition (without protection, in “off” mode and in oral communication mode). The incidence angle of the alarm appeared to have an effect on detection thresholds, with a slight tendency toward lower thresholds (better) in side angles (45–135°), except for broadband alarms, which demonstrate a better threshold at 0° in oral communication mode. Recent data obtained from a University of Connecticut laboratory with a sound restoration earmuff also indicate that the signal direction with respect to the user can affect detection of an alarm in noisy conditions (Giguère et al., 2011a). In some situations, almost perfect detection of the alarm can be realized at frontal incidence, while performance was random for signals presented directly behind, in the same diffuse noise. Such a result may be related to directional characteristics or to the position of external microphones on the headsets. This non-detection could present a significant safety risk because these rear alarms are outside of the worker’s visual field or it is more difficult to effectively couple them with a visual signal.

Data from Casali et al. (2004) about sound detection indicates that hearing protectors such as active noise reducers, for which the attenuation at low frequencies is more substantial than that of passive models, may be advantageous compared to conventional hearing protectors among people with normal hearing in some situations of intense noise that is rich in low frequencies. Such an advantage appears to be related to a reduction in the upward spread of masking toward the frequency of the signal of interest (Casali et al., 2004; Brammer et al., 2008).

To summarize, it appears that sound restoration devices could have an advantage over passive protectors for sound detection and detection distance in silence and at low noise levels. However, this does not seem to be the case for high noise levels (above approximately 80 dB) or for passive hearing protectors with active noise reduction that provide increased attenuation. In these conditions of high noise levels, active sound restoration hearing protectors typically generate detection thresholds similar to those measured without protection or with passive protectors.

6.3.3.2 Sound Localization

There are significant differences in the results of studies on the advantages of active hearing protectors for sound localization. Abel et al. (2007) noted that two types of active sound restoration hearing protectors with integrated communication systems (one being an earmuff type and the other an earplug type) were less harmful than conventional passive protectors in the task of identifying a broadband stimulus transmitted through eight loudspeakers on a horizontal plane. The reduction in performance compared to an unprotected hearing condition was largely due to front/back inversion errors. In a follow-up study, in which interaction between the active earplug and various configurations of a military helmet were observed (Abel et al., 2009), there was relatively less degradation in sound localization compared to unprotected hearing, especially when a helmet was worn. This degradation was related to subtle front/back confusion between sources situated close to the interaural axis, which are less likely to have an impact on operational performance. However, in the study by Brungart et al. (2007), the performance of active sound restoration hearing protectors during a 3-D localization task for broadband stimuli was lower than that obtained with conventional hearing protectors, and was found to be noticeably weaker than in the unprotected condition. The authors noted, however, that the results were well below those obtained previously in their laboratory with a different array of sound restoration protectors.

In a task to localize sound in the presence of traffic noise, Carmichel et al. (2007) evaluated three different sound restoration earmuffs. The results indicate that these devices do not preserve sound localization capacities in most conditions, and that a longer reaction time was necessary for familiar broadband stimuli, compared to an unprotected listening condition. Alali and Casali (2011) studied localization of backup alarms in the presence of pink noise with a range of seven active and passive protectors (earmuffs and earplugs). In general, dichotic sound restoration earmuffs showed no advantage over their passive counterpart and produced slightly weaker results than some passive earplugs in the presence of high noise levels. This difference was attributable to a higher number of front/back errors. Overall, the results did not demonstrate that new hearing protection technologies were better than conventional passive protectors. However, in an additional study using the same methodology, Casali and Alali (2010) demonstrated that, compared to performance in an unprotected condition, performance measured with a sound restoration earplug was not notably reduced.

In a recent study, Giguère et al. (2012a) studied the effect of head movements in identifying the provenance of two backup alarms (tonal and broadband) in the left/right and front/back horizontal plane in the presence of 80 dB noise among people with normal hearing using a sound restoration hearing protector. This data were gathered with and without head movements under three conditions of the sound restoration devices, i.e., in "off" mode (passive attenuation only), oral communication adjustment with a low gain (approximately -6 dB) and with oral communication adjustment with a higher gain (approximately 9 dB). The results demonstrated that movements of the head were particularly helpful in resolving front/back confusion. The performances were slightly better in the unprotected condition, while no statistically significant difference was demonstrated among the three conditions of use of the protectors, which indicates that the sound restoration earmuff neither improved nor reduced sound localization compared to passive attenuation.

6.3.3.3 Speech Perception

Dolan and O'Loughin (2005) studied the effect of a passive protector and three sound restoration devices on sentence recognition among people with sensorineural hearing loss. The speech recognition thresholds in industrial noise of 85 dBA (noise or speech for frontal incidence) were neither improved nor degraded by the passive protector or by active detectors adjusted to the gain preferred by the user compared to conditions without protection, despite major differences in gain among the various hearing protectors.

The impact of both passive and active hearing protectors depends on the experimental conditions investigated. The Giguère et al. study (2011b) supports this finding. Percentages of word recognition were obtained among people with normal hearing and those with hearing loss for speech in frontal incidence in two types of noise generated by military activities and presented in a diffuse 80–90 dB field. Figure 7 shows the difference between the percentages obtained with and without sound restoration earmuffs adjusted to three different gain settings ("off" mode, at low gain and at high gain), among four groups of participants with different hearing profiles. A positive difference indicates an advantage compared to the condition without protection. When the protector is worn in "off" mode, we note that word recognition remains relatively unaltered among people with normal hearing, despite passive attenuation of approximately 30 dB, while it is negatively affected among participants with hearing loss, on a scale that depends on the degree of loss. This observation is in keeping with previous studies on the impact of passive protection. When the device is set to oral communication mode with a low gain (approximately -4 dB), a sizeable advantage is noted compared to "off" mode, with an improvement of approximately 25–60% among all the groups of participants. In oral communication mode with a higher gain (approximately 10 dB), all the groups of participants showed improvement on the order of 20%–30% compared to the condition without protection, which is very encouraging.

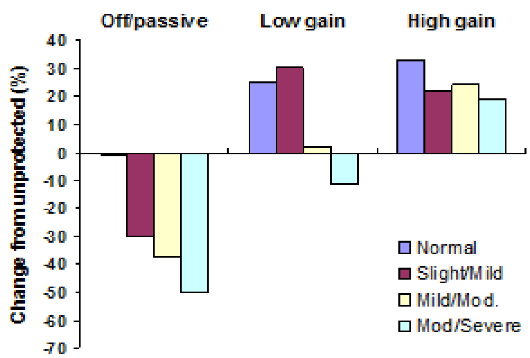

Figure 7 – Difference in percentage of word recognition with a sound restoration earmuff in three modes of use (Off = passive attenuation, Low gain ≈ -4 dB, High gain ≈ 10 dB) compared to a condition without protection, among four groups of participants (from Giguère et al., 2011a)

Data gathered at the University of Connecticut using people with normal hearing in a diffuse field of low pass filtered pink noise demonstrates the effect of the speaker's position when two sound restoration earmuffs are used (figure 8) (Giguère et al., 2011a). There is an advantage of 10% to 15% in the rate of word recognition compared to passive attenuation when speech is face-to-face (frontal incidence), while the opposite occurs when the speech comes from behind. Again, such a result could be related to the directional characteristics or the position of the external microphones on the headphones.

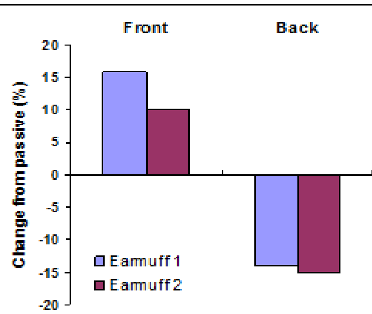

Figure 8 – Difference in the percentage of word recognition with two sound restoration earmuffs compared to passive attenuation for speech that is face-to-face (front) or from behind (back) (From Giguère et al., 2011a)

In the studies cited above, communication from a distance was not considered and all signals (speech and background noise) from the surrounding environment reached the listener's position through acoustic transmission. Therefore, the signal and the noise undergo the same attenuation effects as hearing protectors, whether passive or active. The integrated microphone in active noise reduction (ANR) or sound restoration devices may, however, be supplied with an additional signal from a bidirectional radio, a Bluetooth device or another means of electric or electromagnetic transmission to enable verbal communication from a distance. In that case, the speech signal is transmitted directly by the device's communication channel, without being attenuated by it, while external background noise undergoes ANR, or passive or variable attenuation. One of the key objectives of research in this field is to determine the potential advantage of noise reduction circuits (ANR) and the optimal selection of volume adjustment on headsets to attain better speech recognition and clarity, while limiting the level of sound exposure to the user. For example, in a flight simulation, Casali et al. (2007) studied speech recognition and operational performance when three headsets with ANR and one passive device were used, with speech being transmitted over the device's communication channel. Under adverse conditions, greater recognition (fewer repetitions of orders) was noted with the three active headsets compared to the passive device, and, in three of the four flight performance measurements, one of the active devices provided better results than the others. Furthermore, the pilots felt that there was less mental effort required with the active headsets than with the passive device.

Some studies have demonstrated that the ANR circuit of a communication headset could effectively reduce the level of sound exposure in the ear by approximately 10 dB (5 to 14 dB according to the studies and depending on the noise) (Rogers, 1997; Simpson and King, 1997; McKinley, 2000; James, 2005).

6.3.3.4 Subjective Appreciation of Users

One would think that in improving communications and awareness of the sound environment, active hearing protectors would be preferred over passive protectors by users; however, ease of use and comfort must also be considered when assessing the degree of satisfaction with them. Studies show contradictory results with respect to these two aspects, which could strongly influence usage behaviours for any hearing protector or communication headset.

Ong et al. (2004) compared two active protectors (a sound restoration type and an ANR type) to passive protectors among members of the naval services. Compared to passive protectors, the two active devices were deemed to be more comfortable, durable and effective in reducing sound exposure in the workplace, while enabling better productivity and communication among coworkers. However, the study had one significant limit, in that the devices were worn for only one hour.

In a study by Tufts et al. (2011), workers in a plastic film manufacturing plant compared the passive type typically used in the factory with two sound restoration protectors (one with integrated radio communication and the other without), during 10-day trial periods. Compared to passive protectors, the active protectors were more positively assessed, in terms of communication and awareness of the sound environment, but were viewed less positively when ease-of-use and comfort were assessed. Moreover, the active protector without integrated radio communication was preferred over the one with it because of practical problems related to radio communication.

Williams (2011) observed greater subjective approval by experienced shooting instructors with respect to three sound restoration protector models (including one device with adjustable amplification for each ear and one with Bluetooth connectivity), compared to passive protectors, over a three-month trial period. In general, the instructors reported that the active protectors made it possible to carry on a face-to-face conversation without interfering with target practice, that they were comfortable to use for normal length of time (1.5 to 3.5 hours a day), were easy to adjust, wear and use and that they eliminated undesirable noise while maintaining awareness of the sound environment. However, the instructors felt that the active protectors could be a nuisance and become uncomfortable when they were used all day.

It is therefore clear that, even for active protectors, practical problems related to their use in the workplace must be taken into consideration in order to improve users' approval and acceptance of and satisfaction with them.

6.3.4 Characteristics and Limits of Hearing Protectors

Active protectors provide passive or variable attenuation. Passive attenuation is usually well-documented with the help of NRR or other statistics. A consultation of the websites of various hearing protector manufacturers revealed a multitude of earmuff- and earplug-type products, for which detailed and complete information of the characteristics was not always available. This led us to the conclusion that there is little information available to users to make an informed choice.

Sound restoration devices provide a gain of up to approximately 12–18 dB (according to the model) under relatively quiet conditions and their maximum output is adjusted to ensure sound exposure levels at the ear below 82–85 dBA. These protectors have a range of options to improve communication, both face-to-face (oral communication mode) and at a distance (connectivity with a bidirectional radio, a Bluetooth device, a mobile phone or other external audio sources, in addition to other electric or electromagnetic transmission possibilities). Some models include an ANR circuit for additional attenuation at low frequencies. Volume controls are typically found on active sound restoration products, although few of them are equipped with gain adjustment by frequency bands or independent adjustments of gain for each ear.

While the use of active protectors in noisy workplaces may appear to be a promising option for workers with hearing loss, there are a number of shortcomings with the products available and current practices, which limit their potential. Workers' hearing loss is usually not uniform over all audiometric frequencies. However, most of the products available have a fixed gain curve or one that is relatively flat in frequency. Although some products offer the possibility of adjusting the gain according to the frequency, adjustment flexibility remains limited and does not make it possible to reliably match the individual's hearing loss on the audiogram with what can be obtained with hearing aids. In addition, workers may have unilateral hearing loss (one ear only) or asymmetrical loss (different in each ear). Despite that fact, very few products enable adjustment of the gain for each ear independently, compared to hearing aids, which have this possibility.

It would therefore be a good idea to integrate some of the options available in hearing aids, including directional microphones, into active hearing protectors. The microphone options available in active hearing protectors remain limited, and only a few products with integrated microphones have some directional characteristics.

With respect to active protectors, the programming options for the user or another resource in the workplace are very limited (or nonexistent), and there is no programming platform common to all manufacturers. However, such a programming platform would be useful to customize the hearing protection product according to the specific and individual needs of each worker.

The hearing protector industry does not follow standards as well developed as those that govern the technical specifications of hearing aids, such as the ANSI/ASA S3.22-2009. In fact, manufacturers are not required to report all the characteristics of their hearing protectors. For example, gain characteristics are not always indicated, and some manufacturers specify the release times in milliseconds, while others describe them qualitatively (very slow/slow/normal) or they simply do not provide them at all. Some specify the attack times, but not the release times. In light of these findings, it would be useful to have a standard similar to the ANSI/ASA S3.22-2009 standard for hearing aids applied to the electronic hearing protector industry. This would make it much easier to select products adapted to workers' needs, using a personalized approach.

6.4 Discussion

Among the options available to workers with hearing loss, active hearing protectors, and in particular, sound restoration systems, appear promising, in terms of ensuring adequate protection by improving or preserving awareness of the sound environment and verbal communication capacities. To our knowledge, there are currently no sufficiently well-designed devices to reliably restore awareness of the sound environment to the level obtained without hearing protection in all hearing situations, despite some remarkable technological advances. Furthermore, active hearing protectors have often been studied in very specific hearing situations or fields of work, which makes it difficult to generalize the research results.

For use among workers with hearing loss, there is less flexibility and possibility of customization in the adjustment of active hearing protectors compared to hearing aids. The adjustment options remain limited (very few products provide independent gain setting for each ear, a gain setting to specific frequencies or the possibility of directional microphones), there are no programming platforms common to all of the manufacturers, and the technical specifications are provided very rarely.

The subjective impression of users with regard to sound restoration hearing protectors is generally favourable compared to passive protectors (Casali et al., 2007, Williams 2011, Tufts et al., 2011), although some practical problems related to their use in the workplace should be taken into account in order to increase the levels of approval, acceptance and satisfaction of the users who must wear them. Some obstacles to the use of active protectors remain, such as with respect to their comfort and compatibility with other personal protection equipment. Other obstacles include the costs associated with these systems, their shock resistance, their reliability over time as they are used every day, and their ease of use (e.g., rechargeable or battery-operated systems).

It is important to keep in mind that sound restoration systems differ from passive protectors only under conditions in which the ambient noise does not exceed a certain level of sound pressure. If not, the passive protection dominates and the advantage of active systems diminishes. In workplaces in which ambient noise continually exceeds that level, such systems offer few advantages compared to passive protectors.

Given the relatively recent arrival of these products on the market and the expansion of their use over the years, questions arise about a number of practical applications. For example, in sound restoration systems with integrated remote communication functions, does the signal coming from the environment (oral communication mode) take precedence over the signal transmitted by the radio?

A significant obstacle to the future development and use of active hearing protectors in the workplace lies in the scarcity of technical electroacoustic data provided by the manufacturers, which contrasts with what can be seen among hearing aid manufacturers. Some progress is expected since the enactment of the ANSI/ASA S12.42-2010 standard. However, this new standard only targets the attenuation performances of protectors. Some important parameters in terms of awareness of the sound environment, such as the directional characteristics of microphones, gain by frequency, compression parameters, internal noise and the harmonic distortion present in oral communication and bidirectional radio communication mode were not included. It therefore remains difficult, and sometimes impossible, to associate certain research results to specific technical parameters for a given model of protector. Understanding of these parameters is crucial in order to develop tools to guide the selection of an active hearing protector that will be best adapted to specific situations.

7. SYNTHESIS OF ALL THE PHASES

The general objective of this study was to determine whether wearing hearing aids could reduce hearing, communication and localization problems in noisy workplaces, without aggravating hearing loss or compromising workers' safety. The study also attempted to establish whether other technologies could contribute to maintaining or improving hearing performance at work in complete safety. Four distinct phases were carried out to reach these objectives. Table 8 presents a summary of general findings, needs and comments gathered in each phase. To establish a clear link between these data and the recommendations formulated by the research committee, Table 8 integrates the recommendations, which are formally presented in the following section.

The summary provides this contextual portrait: in Québec, hard-of-hearing workers active in the workplace wonder about using hearing aids at work. The development of signal processing software makes it possible for digital hearing aids to be used under protective earmuffs. Some workers have opted for this practice without receiving information about how safe it is, or they have received conflicting advice, which leaves them feeling confused. These workers seek the means to improve their hearing capacity in order to detect signals, alarms, warnings, and to understand the verbal instructions required to carry out their tasks; they want to stay in contact with their physical and social environment. Already more or less disabled in terms of ability to detect sound because of hearing loss, hard-of-hearing workers are even more disadvantaged when they wear the hearing protection that is obligatory for all workers exposed to high noise levels. They are also more at risk of accidents than their peers because of their hearing disabilities.

Hearing aid use in noisy workplaces prompts concern from hearing health and occupational health and safety professionals, with respect to both the preservation of hearing and the physical safety of all workers (phase 1). Although the general trend has been to discourage the wearing of hearing aids in noisy workplaces to preserve the residual hearing of hard-of-hearing workers, no scientific proof currently supports or negates this fear (phase 2). Neither are there are technical tools to measure exposure levels and the theoretical risk of over-amplification when hearing aids are used in noisy workplaces (phase 2). Moreover, there is no scientific data to establish what contribution hearing aids make in responding to the particular needs of hard-of-hearing workers exposed to noise (phase 3). However, the use of active hearing protectors appears to be an avenue that should be explored in response to these needs in some workplaces (phase 4).

The reality, combined with an almost complete absence of applicable scientific data and an organization of services that does not foster the sharing of information or the establishment of a common vision of socio-professional integration of hard-of-hearing workers explains at least partially the stalemate in which these professionals find themselves. The problem is complex, and the issues of health and safety are real. Professionals desire to be directed by clear evidence-based guidelines. Until strong research-based evidence is available, they eagerly await interim guidelines.

Table 8 – Synthesis of findings, needs and comments expressed and the resulting recommendations

Phase	Findings, needs, comments	Recommendations
Phase 1 Occurrence, practices and tools, needs	• Occurrence undetermined, but indications that this is not a rare situation in Québec. • Tendency to discourage hearing aid use in very noisy workplaces out of fears of aggravating hearing loss, but awareness of the needs and additional effort required by these workers in terms of attention and concentration. • Uneasiness about the physical safety of hard-of-hearing workers and their coworkers. • Lack of tools, clear guidelines and consultation and collaboration processes. • Among the professionals involved, lack of consistency and a shared view of hearing loss and its demands in terms of the socio-occupational integration of hard-of-hearing workers who are active in the labour market.	**1. Establishment of a consensus, in the form of interim guidelines, between the hearing health professionals and workers concerned with this issue. The guidelines would cover all of the relevant factors and how to implement measures to provide better support to hard-of-hearing workers in noisy workplaces.**
	• Need for health professionals to better document the auditory needs related to the tasks to be performed by the hard-of-hearing worker. Be able to draw up an inventory of all the factors in the work environment that interact with hearing aids, including the social dimension and the obligation to use hearing protection. • Need for workers to remain aware of their sound environment, to communicate, to detect audible indicators to carry out their tasks, to know about devices that can help re-establish communication safely, to be conscious of the dangers of not hearing. • Importance for workers to have the information necessary to make informed choices.	
	• Hard-of-hearing workers exposed to noise do not receive the same recommendations or the same follow-up with respect to hearing aid use in the workplace from the various bodies they must deal with (CSST, Régie de l'assurance maladie du Québec [RAMQ], public health network, private consultation with hearing aid specialists, etc.). • Use of measurement tools usually available when hearing aids are fitted: insertion measurements, adjustment of the maximum output level, programming of settings for use in noisy workplaces. These protocols are not adapted for the workplace (levels of ambient noise, types of signals, etc.) **(see recommendation no. 2**). • Need to develop new algorithms to ensure that hearing aids detect signals, and maintain communication abilities without threatening residual hearing **(see recommendations nos. 2, 3).**	

Phase	Findings, needs, comments	Recommendations
Phase 2 Risks of over-amplification	• Not sufficient data or valid and reliable measurement methods to determine whether there is a risk of aggravating hearing loss when hearing aids are worn in the workplace.	**2. Carrying out research into developing a noise exposure measurement method that is valid and that can be easily applied by professionals in situations in which hearing aids are worn in the workplace.**
Phase 3 Effect of amplification on speech perception and hearing localization	• Impossible to determine the contribution of amplification in noisy workplaces on both the execution of tasks and on ensuring the safety of hard-of-hearing workers. In addition, the data do not make it possible to affirm that using hearing aids is a risk to workers' safety. • The results available for the hearing aids on the market are difficult to generalize over the target population because of the numerous parameters that must be taken into account. • Lack of research tools that would make it possible to study hearing abilities, in which all hearing aid parameters are well controlled, including the impact of electronic amplification and the acoustic seal of the earmold on exposure levels.	**3. Perfecting a digital intra-auricular prototype, combining the functions of a hearing aid and a protector to directly measure the level of exposure or the noise "dose."**
Phase 4 New technologies	• Use of active hearing protectors could be considered in less noisy workplaces. • No valid evaluation method on the risk of over-amplification related to the use of active protectors has yet been identified. • The contribution of protectors in effectively restoring communication in a noisy context is unknown. • The lack of adjustment flexibility in these devices is unfortunate. • Identify the range of products and the possibilities of adapting them to the workplace, in addition to their effectiveness in supporting communication **(see recommendation no. 4).**	**4. Measurement of the electroacoustic characteristics of active sound restoration hearing protectors using products available in the North American market, and preparation of a directory for professionals.**

8. RECOMMENDATIONS

The first step in fostering interdisciplinary work among hearing health professionals and the workers concerned would be to establish a consensus around interim guidelines for all of the relevant factors and the measures necessary to ensure better support of hard-of-hearing workers in noisy workplaces. While technical knowledge and measurement methods are always integral to research, a preliminary pooling of information, gathered from actual perceptions and experiences of the issues involved in fitting hearing devices for noisy workplaces, could form the basis of sharing a common objective. Such a consensual process seeks to respect the expertise of each person involved. It could eventually result in defining the roles and responsibilities of each, thus encouraging the development of an integrated solution that best suits the worker.

The development of such a consensus would contribute to the recognition and systemization of the information to be gathered, in terms of noise exposure levels, communication needs, the hearing required to perform tasks, the need for safety, the degree of hearing loss, adjustments to hearing aids, etc. Given that none of the health professionals have all of this information, they must be able to rely on and participate in interdisciplinary collaboration. Being open to other expertise encourages a search for solutions better adapted to the situation. In terms of these solutions, noise reduction at the source should always be prioritized. In addition, the adaptation of workstations, including the use of other sensory modalities (vibrations, visual cues), the modification of work tasks or hearing, communication and localization demands, and the use of complementary amplification strategies, or strategies to find alternatives to amplification should all be examined.

The interim guidelines should be known and acknowledged by the various organizations that govern workplace organization and that provide health services to workers (CNESST, RAMQ). They should be widely disseminated in professional training environments, joint sector-based associations and professional associations, and regularly reviewed according to scientific data dealing with technology and intervention methods, gathered through constant technological monitoring by groups of dedicated professionals. Eventually, through research, these guidelines could develop into a best practices guide.

It is necessary to carry out at least three research projects. The first would aim to develop a valid and easily applicable method for professionals to measure noise exposure when hearing aids are used in the workplace. The objective of the second would be to fine-tune an intra-auricular digital prototype combining the functions of a hearing aid and hearing protector, to learn more about the impact of amplification in noisy workplaces. The third project would consist of measuring the electroacoustic characteristics of active sound restoration hearing protectors on an acoustic manikin or on humans, and to publish a directory of products available on the North American market. Intended for professionals, this directory would make up for the lack of availability of hearing protector technical specifications provided by manufacturers.

In terms of this study, the research team believes that the precautionary principle must be applied. It therefore recommends that hearing aids only be considered as a last recourse, after having considered all the other avenues listed previously. If hearing aid use is the preferred option, the risk of over-amplification and the safety of the worker should systematically be taken into account and managed by all the professionals concerned.

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APPENDIX A - QUESTIONNAIRE

1. Participation in the survey
2. Indicate your field of practice by choosing which one best applies in the context of this study.
3. Indicate your workplace by choosing that or those that apply in the context of this study.
4. What is your gender?
5. What is your age group?
6. How many years of professional experience with workers do you have?
7. What is the administrative region of your workplace?
8. Have you ever been faced with the following situation: A worker with hearing loss, of any nature, degree or origin, who intends to use or who is wondering about using his/her hearing aids in a noisy workplace?
9. Over the past five years, how often have you been faced with such a situation?
10. From which economic sectors do the workers who want to use or who wonder about using hearing aids come from? (Check off up to five sectors).
11. Have you ever been faced with the following situation: A worker with hearing loss, of any nature, degree or origin, who uses his/her hearing aids in a noisy workplace?
12. Over the past five years, how many times have you been faced with this type of situation?
13. From which economic sectors do the workers who use hearing aids come? (Check off up to five sectors).
14. Among workers who use hearing aids in noisy workplaces, do you know if any of them are required to use them by their employer?
15. Over the past five years, how many times have you been faced with this type of situation?
16. Have you ever been faced with the following situation: A worker with hearing loss, of any nature, degree or origin, who does not use his/her hearing aids in a noisy workplace even though a health professional recommends their use or the employer requires it?
17. Over the past five years, how many times have you been faced with this type of situation?
18. Which economic sectors do the workers who do not use their hearing aids (despite a recommendation or an obligation to that effect) come from? (Check off up to five sectors).

19. Have you ever been faced with the following situation: A worker with hearing loss, of any nature, degree or origin, who does not use his/her hearing aids, but who can use another electronic amplification device (FM system, hearing protectors with integrated communication system or another electronic protector)?

20. Over the past five years, how many times have you been faced with this type of situation?

21. If you wish, use the space below to share your comments, observations or concerns about this issue with the research team.

22. Whether or not you have ever been faced with the various scenarios put forward in this survey, would you agree to participate in a focus group (in person or by teleconference) in the future, to deepen understanding of the issue of hearing aid use in noisy workplaces?

23. Will you leave us your contact information?

24. What is your name?

25. What is your telephone number?

26. What is your email address?

27. To ensure it is correct, please repeat your email address.

APPENDIX B - EXTRACTS FROM INFORMATION GATHERED DURING DISCUSSIONS WITH GROUPS OF AUDIOLOGISTS

Origin of request or context, expression of need	Workers' motivation for wearing hearing aids (HA)	Tools, protocols used or interventions	Recommendations to workers	Obstacles	Desired tools or resources	Feeling of professional effectiveness
• When hearing aids (HA) are replaced, when hearing is tested, or for follow up. • Ask people if they can use HA at work. • During a consultation for hearing difficulties in personal life, presence of tinnitus and noisy environments.	• To better communicate with the boss at a factory. • ++ communication needs, use of CB radio. • To keep job: obligation to wear HA at work. • Feeling of safety. • Better performance. • Does not want to be cut off from the surrounding sound environment.	• Global evaluation of needs when case history is gathered (abilities, disabilities) at work and elsewhere, responsibilities, hearing demands, workplace, noise levels if available. • Research noise levels with occupational health team, employer, CLSC, public health or take summary measurements during visit.	• Do not wear HA in noisy workplaces. • First protect your hearing. • Don't forget about their physical safety. • Significant awareness of the worker; he/she must understand the issues and help in finding solutions.	• No standardized tool to assess whether wearing HA is safe. • Worker thinks that digital HA are safe, because of output limitation mechanism or other. • No clear guidelines. • Lack of information to describe working conditions.	• More adaptation of workstation and other strategies to ensure hearing safety. • Take advantage of factory visit. • Have a workplace noise sample (levels + spectra). • Teamwork to combine strengths and more collaboration. • Validation data.	• Concerns about the dangers of over-amplification: how to amplify and be safe? • Wondering about possible modification (spectrum) of environmental signals by amplification? • Wondering about recommendations to be made for people who have been deaf since birth, with HA at work, even if in a ± noisy environment: +++ amplification = hearing deterioration? And safety? ± good awareness of deterioration? E.g., young oral deaf person, who wears HA all the time, starting to work as a mechanic.
• CSST: Since digital HA have been on the market, demand for the workplace (previously, the CSST reserved and paid for digital HA only for work purposes).	• Audiologists agree that the difficulties reported by hard-of-hearing workers are also experienced by workers who are not hard of hearing.	• Document communication needs: manager, foreman (often less exposed, but with ++ needs).	• Recommendation to possibly use in certain areas in the workplace with dedicated program (possibility of using earmold). Do the best with what's available.	• Lack of information about the influence of HA signal processing modes and protection with respect to noise (e.g., noise reducer?)	• Work in partnership with the CSST. • Have intervention protocols. • Have occupational health and safety audiologists.	• Ask what kind or orientation to give to a plumber, mechanic, etc., who uses hearing to determine the source of problems; need their HA, if not, $\neq$ job.

Extracts From Information Gathered During Discussions with the Workers (Hearing Aid Users)

Information requested by hearing health professionals	Instructions received regarding hearing aid (HA) use at work	Why the desire to wear hearing aids (HA) at work?	Benefits or lack thereof reported	Concerns about safety	Avenues for improvement
• Ask who the employer is, but little information requested about the nature of responsibilities at work (e.g., supervision, training, using the telephone, etc.). • We don't really talk about it. We were presented with 3 models and were told that it's that one that's best for you. • Questions were asked about the presence of dust, heat, humidity. • One worker told the hearing aid dispenser that he wanted an automatic model because there was dirt, grease, and oil there, and he didn't want to have to take them off or to push a hearing aid control button.	• No specific instructions: wear HA all the time, but when going to a very noisy department, he takes them off and puts on his earmuffs. Must take them off because the HA cause feedback. It's the amount of noise that makes him decide whether to take them off in a very noisy area. • A worker received instructions from the hearing aid dispenser to not wear his HA at work, except for meetings. • A worker was told to come to his own decision, after being told that HA amplify noise. • No instructions not to wear them. Uses hearing aid control buttons that enable the program to be changed if it is very noisy. His hearing aid dispenser regularly asks whether the noise bothers him and re-adjusts the settings as necessary. • Adaptation of workstation.	• Masks tinnitus. • Better able to hear in meetings. • Better able to follow conversations. • When I don't have my hearing aids, I'm useless. There is always background noise in the factory. • Detect sound, such as an escape from a pipe. • Hear when others call me. • Hear changes in machine noises. Distinguish different sound signals.	• Effective in masking tinnitus. • Hear sounds that I could no longer hear, music. • Lets me lower the volume on the television. • Speak less loudly with HA. • No benefits in the car, when I drive, it cuts out, I can no longer hear my girlfriend.	• Lift conductors must pay more attention. Because of noise, accidents have occurred, even among people with good hearing. • I know that I have to pay even more attention because of my disability, I try to keep my eyes open. I feel that my disability could have an impact on others. I've developed the reflex to be more attentive. • Need to be more alert. • I compensate with my eyes. • Before having HA, he would bump into people when turning, because he had not heard them.	• Know what the results of the hearing screening means. Not just to hear that you'll be deaf in a few years. • Don't wait until I'm over the threshold set in the *Scale of Bodily Injuries* to do something. If I can't be compensated by the CSST, I could perhaps take steps on my own. • When they adjust our HA in the office, they work well, but when we go back to work the next day, they no longer work well. • Could we have a trial HA that we could adjust ourselves so that it suits us and after we could save those adjustments? • Better understand the possibilities of HA and their options.

APPENDIX C – RISK OF AGGRAVATING HEARING LOSS

C.1 Evidence of the Risk of Hearing Loss Aggravation Through Hearing Aid Use

The question as to whether hearing aid use can lead to deterioration in residual hearing has been posed for several decades, and the response to it in the scientific articles is not unanimous. Markides (1971) highlighted this lack of consensus over 40 years ago in a review of the literature on the issue. In fact, the results in articles that present data on the audiometric monitoring of hearing (mainly among groups of individuals) are contradictory.

Authors have focused on the evolution of hearing thresholds over time, either by comparing an initial audiogram to a more recent one, or by comparing thresholds measured at various points in time and afterward quantifying the changes noted in the fitted ear compared to the non-fitted ear. Although some authors report significantly more deterioration in hearing thresholds in the fitted ear than in the non-fitted ear (Macrae and Farrant, 1965; Ross and Lerman, 1967; Macrae, 1968c; Reilly et al., 1981), the results of other studies do not support this conclusion, or are less conclusive (Naunton, 1957; Roberts, 1970; Markides, 1976; Darbyshire, 1976; Titche et al., 1977; Podoshin et al., 1984).

With the exception of a few articles (Naunton 1957; Titche et al., 1977; Podoshin et al., 1984), the groups studied were mainly children with significant sensorineural hearing loss (of various degrees, from moderate to profound). Monaural fitting was more common and enabled the non-fitted ear to be used as a control during comparisons of threshold deterioration between the two ears, over various points in time. It should be noted that the hearing aids investigated were mainly linear analogue devices and rarely included circuits that could limit the maximum output (for example circuits with automatic volume control). For various reasons, the results of these studies cannot be generalized to the population of interest here, workers using hearing aids in noisy environments. It is reasonable to think that this population differs from those of the above-mentioned studies in a number of ways. First, it can be assumed that workers' hearing loss is not as serious. In fact, if one looks at the ISO 1999 (1990) standard's predictions for estimating hearing impairment risk due to noise, it is unlikely that hearing thresholds reach a severe to profound level of hearing loss in workers, who are typically exposed to sound levels below 100 dBA for eight hours, even when age is taken into account. Although personal conditions can be added to the effects of noise among some workers, in most cases, the degree of hearing loss generally associated with occupational hearing loss requires lower levels of amplification (gain) by the hearing aids. In addition, the sound levels to which they are exposed in noisy workplaces are potentially higher than those that characterize the typical sound environment of children. Moreover, bilateral fitting is now more common. Finally, hearing aid technology has made great progress since the publication of many of the above-mentioned articles, which date from the 1960s to the 1990s.

C.2 Methods to Evaluate the Risk of Aggravating Hearing Loss when Hearing Aids Are Used

C.2.1 Risk Evaluation Method Applicable to Groups

Despite the lack of consensus in the results from the studies summarized in phase 2 of the report, we can examine the risk evaluation method used by some authors during studies on groups of individuals, i.e., audiometric monitoring, in order to determine whether this method could be of interest for this study. Despite its simplicity and the use of easy-to-access clinical equipment, a number of weaknesses are associated with this method. We note that an analysis of the group data can easily mask major individual differences (Hawkins, 1982). Thus, it would be possible for an individual's hearing to have significantly deteriorated while the results reported for his/her reference group show no substantial change. Similarly, the changes in thresholds reported in several of these studies are often averaged out over a range of frequencies, making it impossible to pinpoint deterioration at specific frequencies that are potentially more sensitive to noise exposure. Moreover, in a number of cases, the results of a pre-amplification hearing evaluation are unavailable for the purposes of comparison, so the analysis pertains only to the first valid audiogram that is available in the file. The interval between that audiogram and when hearing aids were first fitted is also often not specified, and there could have been deterioration in thresholds even before the audiometric measurements reported were taken. For example, if the first valid audiogram was done a year after fitting and the final audiogram was taken two years later, it is possible that significant deterioration had occurred before the first audiogram, even though the pre- and post-hearing aid comparison reveals no substantial difference in hearing.

In addition, there is often considerable variability among participants in the duration of hearing aid use between the first and last audiogram used for the analysis, from a few months to several years, and even ten years or more. Yet it is reasonable to assume that the amount of deterioration could vary, depending on the duration and frequency of use of hearing aids, much like the phenomenon of hearing loss caused by noise exposure (ISO1999: 1990). This hearing deterioration associated with hearing aid use can develop more rapidly in the first years of use and continue to worsen the longer they are worn. The longer they are used, the greater the possibility that the hearing aid parameters, and indeed the hearing aids themselves, may have changed in the course of the study. These factors could also potentially influence the results.

Other important factors that could have a significant effect on hearing deterioration are not well documented or controlled in these group studies. The factors include the hearing aids' maximum output, gain, volume setting, the presence of a noise reduction algorithm (and other parameters), in addition to the initial degree and nature of the hearing loss. Some authors (e.g., Macrae and Farrant, 1965; Macrae, 1968b; De Vitto and Cruz, 2001) have shown a positive correlation between the degree of hearing deterioration in the fitted ear and the maximum output and/or gain, as well as the volume used, of the hearing aid, and a negative correlation between the degree of deterioration in the fitted ear and hearing thresholds when the device was originally fitted, with a more pronounced initial hearing loss being associated with less serious deterioration. Finally, despite the hearing loss in these studies being mainly of a sensorineural nature, 60% of adults examined by Naunton (1957) had a conductive or mixed loss, with these types of loss possibly being less subject to the effects of exposure to high sound levels than sensorineural losses (Glorig et al., 1961; Sataloff et al., 1962; Chung, 1978; Humes, 1984; Humes and Jesteadt, 1991).

C.2.2 Risk Evaluation Methods Applicable to Individuals

As previously indicated, the group data could mask significant deterioration in a specific individual (Hawkins, 1982). In the scope of this study, we were more concerned with individual hearing deterioration than that of groups of hearing aid users. In the literature, several methods to evaluate the risk of individual aggravation applicable to those using hearing aids were found: (1) individual audiometric monitoring, including the measurement of permanent shifts in hearing thresholds, the measurement of temporary threshold shifts, the measurement of otoacoustic emissions; (2) the estimation of noise exposure levels ($L_{ex,\ 8h}$) using dosimetry, measurements using a coupler or an acoustic manikin and etymotic measurements; (3) predictive models.

The following pages deal with these risk-evaluation methods and sum up some relevant studies.

C.2.2.1 Individual Audiometric Monitoring

C.2.2.1.1 Audiometric Monitoring Through Measurement of Permanent Hearing Threshold Shifts

As with the group studies, the hearing thresholds measured at various points in time can be compared to determine whether a reduction in hearing in the fitted ear can be attributed, at least in part, to over-amplification. Ross and Truex (1965) presented the case of two children in whom significant degradation in the fitted ear was noted over time, but not in the non-fitted ear (a deterioration of approximately 25 to 35 dB over all of the frequencies in the first case), after use of a hearing aid with high maximum output. Although no statistical analysis was carried out, the criteria of 10 dB was used to determine a substantial difference between the thresholds measured over time in both ears.

Roberts (1970) also described the case of a five-year-old boy in whom a drop of 50 dB in high frequencies in the fitted ear was noted, compared to only 10 dB in the non-fitted ear, after approximately three years of hearing aid use. As in several other cases, the parameters of the hearing aid used were not described and many other methodological details were absent.

Hawkins (1982) presented the case of an adult in which a deterioration of 30 to 45 dB was measured over all of the frequencies in the fitted ear, compared to a loss of sensitivity of 15 dB at 1000 Hz and 10 dB at 2000 Hz in the non-fitted ear, over ten years. The gain and the maximum output of the hearing aids used over this period were provided. However, the specific date on which a second hearing aid (bilateral fitting) was introduced was not indicated, even though the analysis went beyond that interval, and acoustic trauma had also occurred at a specific time during the analysis period.

Heffernan and Simons (1979) presented the case of two children in which, after seven months in the first case, and one year in the second case, stability in the thresholds of the non-fitted ear and temporary deterioration in the hearing sensitivity of the fitted ear was noted (5 to 25 dB in the first case, and 20 to 35 dB in the second case). After 14 days of non-use, there was a reversal in the deterioration. In addition, following the introduction of new devices with a lower maximum output and gain, hearing remained stable. The method used by these authors, i.e., measuring thresholds over a short period of time, followed by a period of rest from hearing aid use, made it possible to show that there was a reversible temporary shift in hearing thresholds.

Macrae (1991a; 1996) also used data about permanent threshold shifts in the fitted ear of children wearing powerful hearing aids. In a first case, the permanent threshold shifts in the fitted ear of eight children were compared to the shift predicted by a mathematical model that took estimated levels of noise exposure into consideration. In that study, Macrae (1991a) validated the model (described below) by demonstrating that the shift he predicted was not statistically different than that measured. In a second case, Macrae (1996) used the validated model to determine, in two independent cases, whether permanent shifts in hearing could be attributed to over-amplification instead of to other factors. In both cases, the shift observed was considerably higher than the shift predicted and thus was attributed to a probable progressive hereditary loss in the first case and a fistula in the second case.

Although the comparison of audiograms can be used at an individual level to document the risk of aggravating hearing impairment, there appear to be a number of flaws in this approach, which should be pointed out. Some of these flaws also apply to the audiometric monitoring of hearing commonly used in the scope of hearing loss prevention programs in noisy workplaces. First, because of the measurement error (typically +/- 5 dB in a controlled clinical environment), a change above 10 dB in the thresholds must be obtained before being able to report that there is a considerable difference. Some irreversible hearing loss, even slight, is thus possible before the difference is found to be substantial when the hearing thresholds are measured. If the goal of the intervention is to ensure that there is no deterioration, even minimally, the objective will not be reached in that case. Second, as in the group studies, a valid audiogram is not always available before amplification. Third, in most studies that have used a hearing threshold evaluation, the authors compared the changes noted in the case of the fitted ear when the non-fitted ear was used as a control. Over the past years, bilateral fitting has become ubiquitous to the point that it is now preferred and monaural fitting is discouraged (except in certain specific cases). When an individual uses two hearing aids the possibility of using one ear as a control is lost; it then becomes difficult to distinguish the effect of hearing amplification on hearing from other factors that could affect both ears equally (e.g., disease, spontaneous deterioration of hearing, progression of age-related hearing loss, and progressive loss). Finally, if hearing in one of the two fitted ears deteriorates, consideration must be given to factors such as greater sensitivity to amplification in one ear, or a work environment in which sound exposure in both ears is different (e.g., more pronounced sound exposure in the left ear in the case of a police officer who drives with the window down).

Other factors must also be taken into consideration and controlled during repeated audiometric measurements over time. These include compliance with standards governing the measurement device used (calibration of equipment and type of equipment used, measurement of background noise in the measurement room, etc.), the preparation of the individual for the evaluation (rested hearing, the examination of the external auditory canal, the instructions given, the positioning of headphones, etc.), the method used to measure hearing thresholds, a tympanometry examination (or lack of one), bias in individual response, the examiner’s bias, and the acoustic conditions during the examination, such as level of ambient noise. Measurement of hearing thresholds to determine the risk of over-amplification thus demands very rigorous control of all these factors.

C.2.2.1.2 Audiometric Monitoring Using Temporary Hearing Threshold Shifts

A second approach that uses audiometric monitoring of hearing thresholds is that of the measurement of temporary threshold shifts (TTS). In a pilot study, several times in a single day and over several days, Macrae (1968a,b) measured the hearing thresholds in the fitted ears of four children who used powerful hearing aids at school. A first measurement of the thresholds of each child was carried out at the end of the day (3:00 p.m.) on a Friday afternoon and the hearing aid was not used over the weekend. The hearing was then evaluated again on Monday morning at 9:30 a.m., after which the hearing aid was used in class and at recess until 1:00 p.m. Hearing was evaluated several times before (11:00 a.m.), immediately after (1:00 p.m.) and shortly after (2:00 p.m. and 3:00 p.m.) a period of nonuse of the hearing aid. The results showed an improvement in thresholds between 3:00 p.m. on Friday afternoon and 9:30 a.m. on Monday morning, a deterioration in thresholds over a wide frequency range measured in the fitted ears when the hearing aids were used from 9:30 a.m. to 11:00 a.m., and gradual re-establishment of thresholds afterward, similar to the slow rate of re-establishment found among people with normal hearing. Measurements were also taken using a hearing aid analyzer to quantify the gain of the hearing aids individually.

Despite the methodological gaps (few subjects, no description of the environment in which the thresholds were measured, a population of children versus the population of interest in this study, the absence of statistical analyses, etc.), the method used could be qualified as good for this type of approach. In fact, it enables a clear causal link to be established between the deterioration of thresholds and the use of powerful hearing aids, because we note a recovery in thresholds following a period of nonuse. Moreover, this method could be adequate for cases of bilateral fittings, because it is not the hearing in the fitted ear and the non-fitted ear that is compared, but hearing before and after short periods of hearing aid use.

Macrae (1993, 1994a) also measured thresholds over short periods of time among students wearing powerful hearing aids to document the temporary threshold shifts of hearing in each individual after 4 hours of exposure (hearing aid use) (Macrae, 1993) or 4.1 to 6.7 hours of exposure (Macrae, 1994a). These measurements, combined with dosimetry measurements (to document sound exposure) and measurements of the gain of the hearing aids (etymotic measurements), have made it possible to validate the capacities of a mathematical model to predict the temporary threshold shifts measured in one (Macrae, 1993) or more (Macrae, 1994a) students. The predictive models used by Macrae will be discussed in section C.2.2.3.2.

However, it should be noted that the method of measuring thresholds over short periods described above is different than typical approaches to measure TTS, in which measurements of thresholds are done at specific times, for example, two minutes after the source of noise or amplification stops. This measurement, the TTS-2, is the indicator most often used to predict or quantify the risk of a permanent shift. De Vitto and Cruz (2001) used the TTS-2 in their study of 27 new monaural amplification users with analogue hearing aids, aged between 8 and 49, who had moderate to severe sensorineural hearing loss. The greatest period of use of amplification was six months before the start of the study. In this study, the measurement of hearing thresholds was carried out early in the morning, before the hearing aid was used (pre-exposure measurement), two minutes after approximately seven hours of exposure to an intermittent 78.8 dBA broadband noise in a waiting room (post-exposure measurement or TTS-2), and the next morning after a period of 14 hours of hearing rest (post-rest measurement) without hearing aid use. The response curve of the ear with the hearing aid in place was also evaluated and noise exposure in the waiting room was estimated by dosimetry. Overall, for the fitted ear, an increase (deterioration) in hearing thresholds between the pre-exposure measurement and the TTS-2, and a subsequent improvement between the TTS-2 measurement and the measurement carried out the next morning were noted, with these differences being substantial at certain frequencies. Although etymotic measurements and sound exposure measurements by dosimetry work were carried out, the authors did not attempt to estimate the actual levels of sound exposure by considering the amplification provided by the hearing aid or by comparing those exposure levels with the allowable limits established by various regulatory organizations. The etymotic measurements were only used to attempt to establish correlations between two amplification parameters of the hearing aids, i.e., the input/output response and the real-ear aided gain, and the amount of shift noted in hearing thresholds.

Although such an approach (TTS-2 measurements) may show promise, several weaknesses can be found in the De Vitto and Cruz (2001) article. First, there is no report of the sound exposure conditions the evening before the pre-exposure measurement or the evening before the post-rest measurement. The duration of the hearing rest period before the first measurement is also not mentioned. In addition, the thresholds measured at various times were averaged out over all of the individuals at each audiometric frequency tested, which could mask individual differences or a significant temporary threshold shift in some individuals. In terms of the study's reproducibility and understanding of the methodology, the article is not very descriptive, especially with respect to sound exposure in the waiting room. There is absolutely no information about a test-retest variability indicator, which would make it possible to see whether a shift measured was significant or not. In fact, it is much more difficult to generate a TTS in a more affected ear compared to a normal ear or in an ear with a less hearing loss. The article however, compares the TTS-2 of the fitted ear, which is also the better ear, to the TTS-2 of the non-fitted worse ear. Finally, the article provides no information about free-field equivalent sound levels for the fitted ear, although this information would very useful for establishing the risk of hearing damage linked to exposure to high sound levels.

The other difficulties related to such an approach in a noisy workplace can be raised, in addition to some factors listed in the last paragraph of section C.2.2.1.1, dealing with the measurement of permanent threshold shifts. Among them, it may be difficult, even impossible, to measure hearing thresholds at specific moments such as the TTS-2 indicator, while ensuring adequate and reproducible measurement conditions, especially since pre-exposure measurements (before the work shift) should be made.

C.2.2.1.3 Audiometric Monitoring by Measurement of Otoacoustic Emissions

Like hearing threshold shifts, the disappearance or modification of otoacoustic emissions may also signal the appearance of damage to structures in the hearing system, particularly the outer hair cells, which are more sensitive to damage after exposure to loud noises or ototoxic products (Dancer et al., 1990).

In a case study of a two-year-old girl with hearing neuropathy accompanied by bilateral hearing loss, Kundu and Rout (2010) evaluated the impact of using a conventional powerful hearing aid on otoacoustic emissions. In a first hearing evaluation, there was moderate to severe loss during audiometry by observation, distortion product otoacoustic emissions were present, and the V wave was absent for the measurement of auditory brain stem response, the latter two results being indicative of hearing neuropathy. Hearing aids were then recommended. On the basis of results obtained during a re-evaluation one year later, i.e., a failure in the otoacoustic emissions test and moderately severe to severe hearing loss, a two-week period without amplification was recommended, after which the otoacoustic emissions were sufficiently restored to enable the test to be passed. The authors therefore concluded that a powerful hearing aid could lead to a disappearance of the otoacoustic emissions, and frequent monitoring, including the measurement of emissions was strongly recommended.

Although the above-mentioned case of hearing neuropathy does not apply to workers exposed in noisy environments that could damage their outer hair cells, one could question the usefulness of measuring otoacoustic emissions to estimate the risk of hearing damage among those who wear hearing aids in noisy workplaces. There are some limits related to such a measurement tool, with the most important being that otoacoustic emissions depend on the integrity of outer hair cells and are generally reduced or absent in cochlear hearing loss of over 40 to 60 dB HL (Collet et al., 1989; Harris, 1990; Gorga et al., 1997; Kemp 2002). Their use would therefore be limited in cases of normal hearing or of slight to moderate sensorineural losses, while one would expect greater hearing loss among workers who must or who choose to wear hearing aids in noisy workplaces.

In a report recently submitted to the Health and Safety Executive (HSE, 2011) by a group of experts who studied the usefulness of measuring otoacoustic emissions in the scope of audiometric monitoring programs in noisy workplaces, we note the following: (1) for audiometric thresholds above 30–40 dB, accurate diagnostic information is difficult to obtain, and (2) the measurement of otoacoustic emissions would be particularly useful for the early detection of hearing loss, because changes in the emissions occur more rapidly than changes in the audiometric thresholds. In addition, Cilento et al. (2003) indicate that the use of distortion product otoacoustic emissions in the scope of a screening evaluation or to monitor hearing must take factors such as age, gender, hearing thresholds and noise exposure into account.

In order to evaluate hearing thresholds, it is also important to note that an audiometric test booth is necessary, which is not the case for the measurement of emissions. A relatively quiet environment is, however, required because background noise can interfere with the measurements. As with hearing threshold measurement, the evaluation of otoacoustic emissions must be carried out in a controlled sound environment that remains about the same from one measurement to the other in the same individual. A correlation was not clearly established between hearing threshold shifts and the changes noted in otoacoustic emissions following noise exposure (Müller et Janssen, 2008; Helleman et Dreschler, 2012), thus limiting the potential of the test to monitor individuals at risk. Hearing deterioration may sometimes be accompanied by a local increase in the amplitude of otoacoustic emissions instead of a reduction of the response (Helleman and Dreschler, 2012).

For all the reasons given above, the measurement of otoacoustic emissions does not appear to be an optimal tool for quantifying the risk of over-amplification among workers wearing hearing aids in noisy workplaces.

C.2.2.2 Estimate of Noise Exposure Levels ($L_{ex, 8h}$) Using Dosimetry, by Measurements Taken with a Coupler or an Acoustic Manikin and by Etymotic Measurements

Before reporting on the specific methodologies found in various articles (see section C.2.2.2.6), a general description of different approaches that are potentially applicable to hearing aids is essential. The typical methods used to estimate levels of noise exposure in a noisy workplace, through a sound level meter or dosimeter (CSA Z107.56-13; ANSI S12.19 – 1996 R2011), are not directly applicable to situations in which the worker wears a hearing aid or any other device that covers the ear or blocks the auditory canal. In such cases, the sound levels in the ear, behind the device, should be measured or estimated and then adjusted to the equivalent free or diffuse field at the position of the absent worker in order to be compared to regulatory limits, which makes it possible to evaluate the risk of aggravating hearing loss, in the same way as any other source of noise that is a distance from a worker.

Giguère et al. (2012b) did an exhaustive review of the various sound level measurement methods for an occluded ear and the relevant standards, particularly with respect to sound exposure related to communication headsets and headphones. The methods most directly applicable to the hearing aid issue are the use of a microphone in the ear (MIRE – Microphone in a Real Ear), an acoustic manikin and an artificial ear. In each case, the exposure levels must be corrected to obtain their sound field equivalent (ISO 11904) and be expressed in dBA. These methods were recently integrated into the Canadian standard on the measurement of occupational noise exposure (CSA Z107.56-13) and are described in sections C.2.2.2.1 to C.2.2.2.3 below. By extension, although not dealt with by Giguère et al. (2012b) and CSA Z107.56-13, HA-1 and HA-2 type couplers, often used in the analysis of hearing aids, could also be considered, as described in section C.2.2.2.4. In addition, the various methods discussed here presume that the sound level measured at the eardrum is directly related to the risk of hearing impairment, that the source is situated in a sound field that is a distance from the worker (e.g., a machine) or in the ear (e.g., earphone). Some methods question this premise, which will be dealt with in section C.2.2.2.5.

C.2.2.2.1 Microphone in the Ear

The ISO 11904-1 standard describes the measurement of exposure levels in the human ear using a miniature or probe microphone in the auditory canal, linked to a measurement instrument. Acoustic measurements carried out in one-third octave bands at one of the three positions of the probe in the ear are transformed into the equivalent free or diffuse field (ISO 11904-1), expressed in dBA. Although the transfer functions enabling this transformation are provided by the standard for three microphone placement conditions (at the eardrum in an open ear, at the opening of the auditory canal in an open ear, and at the opening of the external auditory canal blocked by the device), it is possible to experimentally determine the transfer functions specific to each individual and ear for various microphone positions. In the case of hearing aids, the only practicable placement is that of the microphone at the eardrum.

In that approach, the correction factors for one-third octave band sound field conversions (ISO 11904-1) are subtracted from the values measured at the eardrum. The resulting values are then converted into dBA using the IEC 61672-1 standard and added logarithmically to obtain a value corresponding to the level of sound exposure in dBA. Finally, if the response in frequency of the measurement microphone is not uniform over all of the frequencies, additional corrections are required.

For individual workers, this method best represents sound exposure actually found in the workplace, because the measurement system records sound level directly in the worker’s auditory canal when he or she is performing various tasks. The method also takes into account all noise sources, the potential effect of reflection off various walls, and other acoustic phenomena, on the cumulative level of exposure. However, for it to be applicable to groups of workers, measurements must be carried out on several of them in order to estimate the average exposure level. Despite its representativeness, a number of disadvantages are associated with this measurement method. As it is invasive (a probe placed near the eardrum), it may limit workers’ movements, even preventing them from carrying out certain tasks. Its use is therefore limited, or even impossible, in some workplaces, especially over long periods and if the worker is continually moving. Only well-trained experimenters can use this approach, to ensure safe and adequate placement of the microphone or the probe. In fact bad positioning of a microphone can lead to significant errors in the calculation of sound exposure and/or become a source of discomfort for the worker. Furthermore, calibration of miniature microphones or probes may be difficult. Finally, the internal noise of the microphone or rubbing sounds between the probe and the device could interfere with the measurement of acoustic levels, as could acoustic leakage caused by the seal being compromised by the presence of a probe in the external auditory canal.

C.2.2.2.2 Acoustic Manikin

The ISO 11904-2 standard deals with use of an acoustic manikin. It is made up of an artificial ear (2cc coupler + microphone), and a flexible pinna, and external auditory channel and a head (and torso) reproducing the average geometry and dimensions of the typical human ear. In this case, the positioning of the microphone does not constitute a source of error because of its fixed placement in the simulated ear of the manikin, which is placed in the same background noise environment as the worker. A new model equipped with a flexible external auditory canal is described in the ANSI 12.42 standard.

As for the method to use a microphone in the auditory canal, the correction factors for one-third octave band sound field conversion (ISO 11904-2) are subtracted from the values measured by the manikin’s microphone. The resulting values are then converted into dBA using the IEC 61672-1 standard and added logarithmically in order to obtain a value corresponding to the sound exposure level in dBA.

This method can be applied to estimate the sound exposure level among groups of workers and has the advantage of not being very invasive, thus making it possible for the person to work as freely as possible in his or her workplace and not be constrained by microphones placed in the ears and attached to a measurement instrument. It is, however, somewhat inconvenient, in part because of cumbersome equipment and instrumentation that are not accessible to everyone. As the device (in this case, the hearing aid) is not worn by the worker, the volume (and other adjustable parameters) is adjusted to the same level as that typically used by the worker in his or her workplace. This constraint could be problematic in cases in which workers frequently adjust their hearing aids during a typical workday. The coupling between the device and the manikin could also be different than that in the worker's ear because of differences in the geometry and the acoustic-mechanic properties between the worker and the manikin. Repeated measurements to reposition the device are, in fact, strongly encouraged in order to average out the effective placement. The ANSI S3.35-2010 standard describes the process for ensuring optimal coupling between the hearing aid and the manikin. It is important that the manikin be exposed to the same ambient noise as a worker. In some workplaces and for some noise sources, the sound ambience perceived by the worker's ear could be difficult to reproduce in the manikin's ear.

C.2.2.2.3 Artificial Ear

Because of constraints related to access to the specialized equipment necessary to perform measurements using a microphone in the ear or in the acoustic manikin, it is sometimes preferable to use an artificial ear.

The IEC 60318-4 occluded ear simulator is a Type 2 (ITU-T P.57) artificial ear commonly used for the calibration of intra-auricular devices. When combined with a flexible pinna and an extension to simulate the external auditory canal, it is instead more of a Type 3.3 (ITU-T P.57) artificial ear, which meets the same specifications as the components found in the acoustic manikin (identical ear geometry, acoustic properties and couplers). The measurements carried out with these two types of artificial ear are then converted into equivalent free or diffuse free fields using the transfer functions specified in the ISO 11904-2 standard and then expressed in dBA. As it is more easily accessible, less expensive, easier to transport and handle in the work environment than an acoustic manikin, the artificial ear, like the manikin, must, however, be exposed to the same sound environment as the worker, which is sometimes difficult to reproduce.

C.2.2.2.4 HA-1 and HA-2 Couplers

The 2cc HA-1 and HA-2-type couplers typically used to measure the performance of hearing aids can also be useful in applications related to noise measurement. Hearing aids, programmed according to parameters generally used by the worker, could be attached acoustically to the dosimeter (or sound level meter) through an HA-1 or HA-2 coupler. The measurement microphone, coupled with the hearing aid, should be worn on the shoulder in the position prescribed for sound exposure measurements using a dosimeter (ANSI S12.19 – 1996 R2011). The values obtained at the coupler must be first transformed into values at the eardrum, then converted into the equivalent sound field, and then expressed in dBA. The correction factors proposed in Table 1 in the Bentler and Pavlovic (1989) article are very useful in this regard, particularly columns A (free field to eardrum), F (2cc to eardrum) and G (2cc to free field). Figure C1 illustrates three different approaches to the application of correction factors to obtain sound exposure values in dBA.

To transform the values obtained with the coupler into values that apply to the eardrum, group or individual correction factors can be applied, and these can be determined by *in situ* measurements of the difference between the coupler and the eardrum (real-ear-to-coupler difference). The *in situ* measurements of hearing aid performance are described in the ANSI S3.46-1997 (R2007) standard.

Although the use of such a coupler could be effective in measuring sound exposure levels in the field, the procedure must be well established. Good positioning of the hearing aid on the shoulder is crucial to ensure optimal functioning of the directional microphones and to avoid the microphone rubbing against clothing and the Larsen effect.

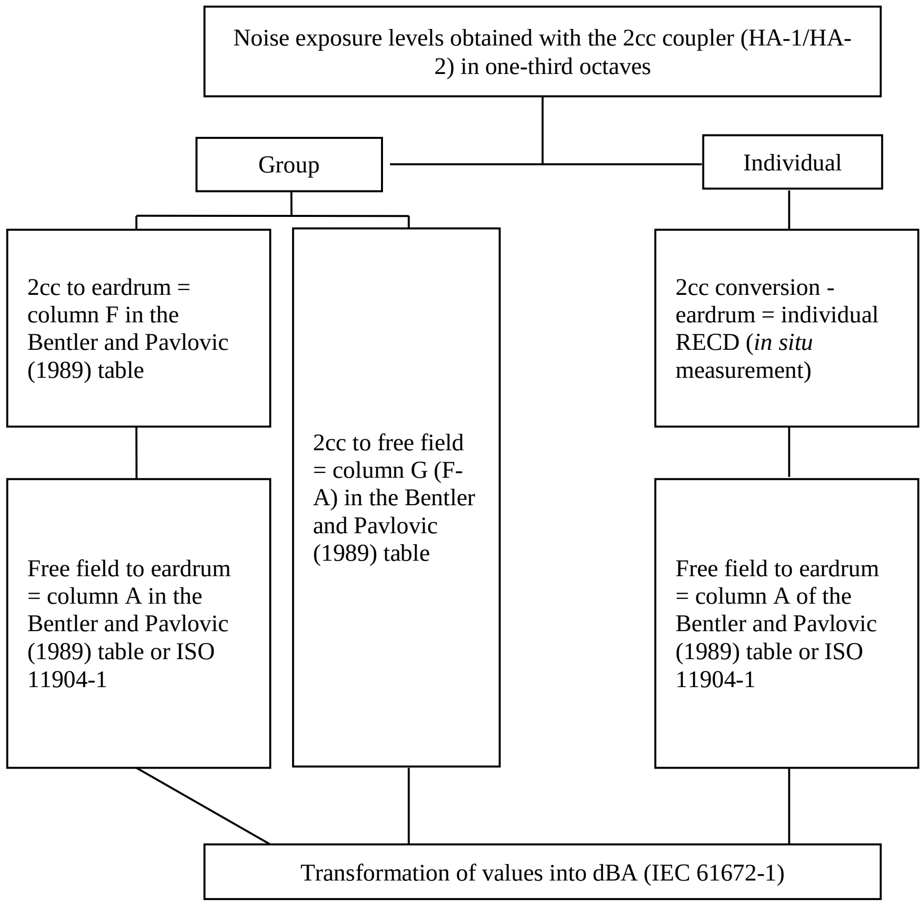

Figure C1 Various approaches to transfer the sound values obtained with a 2cc coupler (HA-1/HA-2) into dBA

C.2.2.2.5 Validity of Measurements in an Occluded Ear Situation

In the approaches described above, one-third octave measurements are taken over the duration of the exposure, transformed into values in the sound field, and finally converted into dBA. One would then assume that the sound level measured close to the eardrum in an occluded auditory canal and transformed into its equivalent sound field is as dangerous as the identical sound level measured directly in the sound field. However, some studies question this assumption. For example, Keidser et al. (2000) demonstrated that the loudness of certain sounds differs according to whether the stimuli come through a loudspeaker (sound field) or a hearing aid (occluded ear); the signal level must be greater in the occluded ear than in the sound field in order to be as loud.

More recently, Theis et al. (2012) have reported significant differences in the risk of sound exposure from an external source (in the sound field) and from a source placed in the external auditory canal (for example, an earphone or a hearing aid). For the same sound level measured near the eardrum, the external source would generate a greater TTS than the sound emitted by an earphone. The measurement of sound levels near the eardrum, in the presence of a sound source in the auditory canal, would then result in an overestimation of the noise exposure level. In the case of hearing aids worn by workers, such an approach should therefore be more conservative. However, would it not be better to overestimate than to underestimate the noise exposure level actually received?

C.2.2.2.6 Relevant Studies

Following this general description of the various methods available, it is now essential to investigate the methodologies used and results reported in various articles.

In 1990, Wilde attempted to quantify the noise exposure level (or equivalent dose) to which children with profound hearing loss were exposed during normal activities in an acoustically treated classroom in a school for deaf children. The goal of the study was to verify whether there was a risk of aggravation of hearing loss among children who were using significant amplification. Electroacoustic measurements were first carried out to describe the maximum output and gain of two different behind-the-ear hearing aids, at the volume set (3.5 out of a maximum volume of 4), when adjusted to various levels of maximum output. The hearing aid was then hooked up to a dosimeter using a HA-2 2cc coupler and #13 tubing; this measurement system enabled quantification of the noise exposure level as amplified by the hearing aid. A second dosimeter estimated the sound exposure levels without amplification. The two dosimeters incorporated correction factors specified in the IEC 651 standard to convert values into dBA. Measurements were repeated for each combination of hearing aid model and adjustment of the maximum output. Measurements carried out over 15 to 60 minute intervals, in which the experimenter “wore” the hearing aid, revealed noise exposure levels varying between 108 and 118 dBA, much higher than the regulatory limit of 90 dBA for eight hours of exposure (LAeq,8h) noted in the article.

Based on the data, the author stated that even in an acoustically treated classroom, a 90-dBA/8 hr. noise exposure level can be reached within one or two minutes when powerful hearing aids are worn, even though the sound level measured by the second dosimeter never surpasses the regulatory limit. It was, however, difficult to determine how the measurement system was “worn” by the individual in question (we presume on the shoulder) and where the experimenter was positioned in terms of the sound sources. In addition, it is not explicitly reported whether the levels obtained with the measurement system (dosimeter + 2cc coupler) were corrected to obtain sound levels in free field equivalent (2cc conversion–sound field). Since the authors used the terminology *equivalent continuous level* in the discussion, one would surmise that such corrections were carried out. Moreover, the risk criteria and regulatory limits are generally based on a population of individuals with normal pre-exposure hearing, but it is reasonable to think that the threshold shifts measured following any kind of sound exposure would be lower in the case of pre-existing hearing loss than with normal hearing. This latter point is mentioned in the article, and the authors attempted to take this into account by comparing their data with those found in studies by Humes and Bess (1981) about the effect of pre-existing hearing loss on the amount of hearing threshold shift. It should also be noted that a noise exposure level below regulatory limits is not safe for everyone, and harm depends on individual sensitivity, among other factors (Plontke et Zenner, 2004; Śliwińska-Kowalska et al., 2006).

In his study of eight children with sensorineural hearing loss, Macrae (1991a) attempted to estimate the noise exposure levels of each when hearing aids were worn by taking the following factors into account: (1) the hearing aid parameters (gain, strength, frequency response, maximum output and volume used by the child); (2) sound levels (dB SPL), in terms of one-third octaves, for a typical environment (measured using an integrating-averaging sound level meter in a room with open windows, thus providing access to street noise, while the person taking the measurements was speaking with other individuals and wearing the sound level meter microphone close to her/his ear), and (3) the number of hours the hearing aid was used per day. In order to estimate the sound exposure levels for each child, Macrae first assessed the one-third octave levels generated by the hearing aid in a 2cc coupler by adding the gain obtained at various frequencies in the 2 cc coupler (at the volume used by the child) to the one-third octave levels measured using a sound level meter, while taking into account the maximum output of the hearing aid when appropriate. These values were then corrected using an average correction factor (2cc conversion-etymotic) to estimate the levels actually generated in the ear of each child. These levels measured at the eardrum were ultimately used to calculate the equivalent overall LAeq level and the equivalent octave band levels generated by the hearing aid in the ear of each child. However, it was not clear whether a correction of the levels was done to produce equivalent sound levels in free field or whether this correction was necessary in the mathematical model (see section C.2.2.3.2) used by the author to predict the expected shift (the correction would not be necessary if the risk values expressed in the equivalent free field were transformed into the values that applied to the eardrum in the predictive model).

In their article, De Vitto and Cruz (2001) also carried out *in situ* etymotic measurements of the fitted gain (real-ear aided gain) and the input-output function of the hearing aid, in addition to estimating the input function of the hearing aid, using a dosimeter with the microphone placed as close as possible to the hearing aid. However, it is strange that the authors did not use such data to calculate the actual noise exposure levels. Instead, they seemed content to evaluate the input sound level at the hearing aids only, without reporting the sound exposure values that applied to the eardrum or their equivalent free fields.

With respect, more specifically, to the population of interest targeted by the study (workers in noisy environments), only a few studies attempted to determine the risk associated with hearing aid use by taking noise exposure levels at work into account. In a first study, Dolan and Maurer (1996), using measurements taken in the laboratory or in the field, investigated whether exposure in compliance with the regulatory limits set by the Occupational Safety and Health Administration (OSHA) (1983), i.e., a maximum noise exposure level of 90 dBA (Q=5 dB), could be amplified to levels above these limits when hearing aids are worn in noisy workplaces, and in non-occupational sound environments.

For the laboratory measurements, recordings made using a digital recorder in two work environments in which noise exposure levels did not go over 85 dBA (the driver cab of a train and a hydraulic pump plant) were re-created in an acoustic chamber. The output of various hearing aids (low, medium and high gain) in linear mode (without compression) were measured using a BandK 4128 artificial head (acoustic manikin), placed at 1 m directly in front of the loudspeaker used to generate the noise. A frequency equalizer made it possible to correct the frequency response of the artificial head, making it more uniform in frequencies and thus more similar to those of microphones typically used in dosimetry. Thus, the values measured could be more directly compared to the sound field exposure values recommended by the OSHA. Non-fitted measurements were also obtained using a microphone placed on the shoulder of the manikin, at 15 cm from the pinna. The level of non-fitted noise exposure (ambient sound levels projected over an eight-hour period) rose to 79.7 and 77.8 dBA for the train and factory noise, respectively. For the three types of hearing aids, the noise exposure level calculated was 92.1, 99.9, and 115 dBA for the train noise, and 86.6, 107.9 and 113.1 for the factory noise. Thus, with the exception of one condition, the ambient noise was amplified by the hearing aids to levels higher than the OSHA recommendation.

For measurements in the field, each hearing aid was coupled acoustically to the microphone of a dosimeter using an HA-1 2cc coupler and impression material to keep the hearing aid or the earmold in place. A second dosimeter, also worn on the subject's shoulder when measurements were taken in a factory during three eight-hour work shifts, simultaneously recorded the ambient levels. The noise exposure level rose to between 82.6 and 84.1 dBA without hearing aids and exceeded 90 dBA with all the hearing aids (91.8, 104.6 and 115.4 dBA). However, the authors do not explicitly mention whether the values measured with the measurement system consisting of a dosimeter + coupler + hearing aid were corrected to equivalent sound field in order to compare them with the values measured using the second dosimeter and the OSHA values.

Dolan and Maurer (1996) concluded that, in a noisy workplace that respects the regulatory limits established by the OSHA, amplified noise exposure levels can go over 90 dBA, even when using a low-gain hearing aid. Again, using a dosimeter, the noise exposure level was also calculated when hearing aids are used in various nonindustrial environments, such as a family get-together (63.1 dBA without and 103.4 dBA with high-gain hearing aids [average gain = 41.3 dB]), during daily activities that are not noisy (61.3 dBA without and 88 dBA with hearing aids with average gain [average gain = 31.5 dB]) and during noisy daily activities (75.7 dBA without and 101.1 dBA with high gain hearing aids [average gain = 41.3 dB]). According to the authors, hearing aid use could also lead to high doses, even in the presence of nonindustrial noises typical of daily activities. Finally, additional measurements in the laboratory using train noises were performed to quantify the effect of modifying certain parameters of a high-gain hearing aid equipped with an automatic gain control circuit (AGC). When the AGC circuit was deactivated and the frequency response was as broad as possible, a noise exposure level of 115 dBA was obtained. That dose can, however, be lowered to 104.3 dBA by maximally activating the AGC circuit and by adjusting the frequency controls to reduce low frequencies as much as possible, which means that the hearing aid will operate less often in a state of saturation. Finally, by decreasing the volume by half in terms of this last condition, the dose is reduced to 54.1 dBA and the saturation is absent.

The results thus tend to demonstrate that the noise level a worker is exposed to could be reduced significantly by using an AGC circuit, decreasing the frequency response of the hearing aid and lowering the volume. Finally, the authors demonstrated that a deactivated hearing aid, for which the earmold occludes the auditory canal in the artificial head of the BandK 4128 manikin, makes it possible to reduce sound levels by approximately 20 dB. It then appears that in passive mode the hearing aid could act as a hearing protector. The results of the study demonstrate that the levels recommended can be exceeded when hearing aids are worn, both in the workplace and in everyday environments. However, the authors caution that hearing aids are often worn for longer than eight hours, which exposes the workers to potentially more significant doses. They add that the risk criteria commonly used are based on normal hearing and cannot, therefore, be directly applied to people with hearing loss. Moreover, a single criterion cannot be applied to all hearing aid users, given that the risk of a temporary threshold shift (TTS) or a permanent threshold shift (PTS) would depend on the degree of the pre-existing hearing loss.

In a second study, Dolan and Wonderlick, (2000) compared the effect of three forms of compression (compression limiting, compression of low frequencies only (BILL) and compression of high frequencies only (TILL) on levels of noise exposure and speech intelligibility of 13 individuals with hearing loss on high frequencies when using a digital hearing aid programmed along three compression modes and worn in the ear with the best thresholds. In order to estimate the noise exposure level, an approach similar to that of Dolan and Maurer (1996) was used, i.e., a hearing aid acoustically coupled to the microphone of a dosimeter through an HA-2 coupler and placed on the shoulder of an artificial head in the same way it would typically be placed when monitoring sound levels with dosimetry in workplaces (i.e., at 15 cm from the concha). During these final measurements, the gain of the hearing aid was adjusted according to values prescribed for the average audiogram of individuals. The dose obtained in various compression conditions rose to 104 dBA for compression limiting and for BILL, and to 94 dBA for TILL. A high compression threshold explains the high dose for compression limiting. According to the study results, the TILL system seems more advantageous for reducing the dose, while enabling word recognition similar to that of a system that operates in a typically linear manner. While this statement may be controversial, the group of researchers noted once again that a noise exposure level that exceeds 90 dBA does not necessarily represent a risk to the hearing of individuals with hearing loss, because the risk criteria commonly used are usually based on normal hearing and well-adjusted devices are generally considered safe. However, they recommended that the worker’s hearing thresholds be tested before and after the workday to identify the presence of a temporary threshold shift and if necessary, they suggest the use of hearing protectors.

In 2006, Paré simultaneously measured the sound levels at the eardrum (with a probe in the auditory canal) and at the entrance of the auditory canal, using a hearing aid analyzer (Audioscan) of a crusher operator in a quarry who wore in-the-ear hearing aids, with an activated noise reduction algorithm. The noise exposure level actually experienced by the worker could not be calculated because of the absence of correction factors to transform the sound levels measured near the eardrum into equivalent free field. Although the hearing aids appear to contribute to increasing sound exposure levels, despite an activated noise reducer, the author acknowledged that she could not determine the risk associated with hearing aid use in a noisy workplace by directly comparing the sound levels measured close to the eardrum with the limits of safe exposure based on sound field measurements. The author pointed out other limits regarding the use of such a measurement system, i.e., that the duration of sweep frequency limits its utility to noises of a sufficiently long duration, and that the system cannot be used in complex environments or those in which the worker must frequently move around.

C.2.2.3 Predictive Models

In order to evaluate the risk of aggravation of hearing loss among hearing aid users, some authors have used mathematical models to either predict sound exposure levels or the deterioration of hearing thresholds.

C.2.2.3.1 Prediction of Sound Exposure

Verbsky (2002, 2003, 2004) developed a method that is an extension of the octave band method for predicting the sound level under hearing protectors (e.g., CSA Z94.2-F14) applicable to hearing aids with and without protectors. She explored the use of an active hearing aid in combination with an earmuff-type protector in noisy workplaces, and discussed a quantitative model for predicting the gain levels of the hearing aid that are considered safe, by taking into account the sound exposure levels and the attenuation enabled by the hearing protector.

This quantitative model makes it possible predict the sound attenuation of the earmuff and the gain of the hearing aid, measured or calculated according to NAL-R, for each frequency between 125 and 125 et 8000 Hz, on the basis of noise levels (dB SPL). The model also takes into account correction factors for the frequency response of the microphone and for resonance in the concha. The assumed protected values (ISO 4869-2, 1994), published by the manufacturers and obtained in the laboratory using subjects familiar with hearing aid adjustment are first subtracted from the noise levels to which the worker is exposed. The result of this step is translated into sound levels under the protector without the influence of the hearing aid. The measured or calculated gain values (NAL-R) are added to these levels to obtain the sound levels with the hearing aid worn under the hearing protector. Then, these values are corrected to take into account (1) the differences between the probe-type microphone used in measuring the gain and the one used in the sound field, and (2) the resonance effects of the concha (according to Shaw, 1974). Using the model, the maximum gain levels of the hearing aid that are considered safe can also be calculated by subtracting the sound levels with hearing aids under hearing protectors from the maximum levels of sound exposure allowed.

The maximum allowable sound exposure levels are defined as the response measured in the non-occluded year exposed to noise on a flat spectrum of 85 dBA, an exposure level that, according to OSHA (1983), does not require the use of hearing protectors in the workplace. The belief is that sound exposure should not constitute a risk of hearing damage if the output of the hearing aid in the hearing canal does not exceed the maximum allowable levels. The values predicted by the model were very similar to the values measured with linear hearing aids under earmuffs with uniform attenuation coupled with an artificial head, in response to a 90 dBA noise with a flat spectrum. Because the values measured and predicted do not exceed the maximum allowable values, the user could be adequately protected in that condition, despite wearing hearing aids under earmuffs. This conclusion does not necessarily apply to all noise conditions, hearing aid gain and hearing protection and would appear to require validation.

Some individuals are vulnerable to hearing damage at exposure levels below 85 dBA. Thus, even if safe gain levels are predicted using a quantitative model, Verbsky (2004) recommends closely monitoring individuals who use hearing aids with hearing protection in the workplace, particularly during the first days of use, in order to rapidly detect temporary or permanent threshold shifts. The estimation of sound exposure levels is a promising approach for documenting the risk of hearing aid over-amplification. It would appear, however, that the utility of such an approach could be limited by two interrelated factors, (1) the necessity of transforming the values measured close to the eardrum with the activated hearing aid into equivalent sound field, and (2) the fact that commonly used risk criteria are typically based on the effect of sound exposure on individuals with normal hearing. In the case of wearing a hearing aid under a protector, the choice of the protector's sound attenuation values, i.e., those measured in the laboratory or in the field, should be questioned. Additional corrections are required when there is pre-existing hearing loss.

C.2.2.3.2 Predicting Aggravation of Hearing Loss

The first attempt to develop guidelines to limit the risk of hearing damage by over-amplification dates from studies by Humes and Bess in 1981. Using an existing model to estimate the permanent threshold shift due to noise exposure among adults with normal hearing (Kraak et al., 1974), Humes and Bess (1981) attempted to apply the model to individuals with hearing loss to establish critical levels that could not be exceeded in terms of hearing aid output, to avoid damage to residual hearing. The hypothesis used to adapt the model assumes that exposure to noise will not damage the hearing of an individual with sensorineural hearing loss, unless the hearing loss resulting from this type of exposure in a person with normal hearing is greater than the loss of this specific individual.

The sound levels to which hearing aid users are exposed are also taken into account in all of Macrae's studies, which deal with the use of mathematical models that make it possible to predict the size of temporary or permanent threshold shifts associated with hearing aid use.

In the Macrae study (1991a) described above (section C.2.2.2.6), the estimated levels of the actual output of the device in the ear were used to predict the amount of expected permanent threshold shift (PTS) in each of the eight children due to hearing aid use. Macrae compared the Humes and Bess (1981) hypothesis with that of the Modified Power Law (MPL) model (Humes and Jesteadt, 1991) combined with Kraak's (1981) equations in predicting permanent threshold shift. These equations took the combined effect of age and noise exposure into account to predict the amount of expected PTS among adults with normal hearing, while the MPL includes a correction for people with sensorineural hearing loss. Contrary to the initial Humes and Bess (1981) hypothesis, the MPL assumes that all noise exposure that could lead to hearing damage among adults with normal hearing could also be harmful to those with sensorineural hearing loss. However, for the same exposure, the degree of deterioration in thresholds and the extent of individual susceptibility to damage will lessen according to the initial degree of hearing loss. This is a nonlinear and non-additive model. Thus, in order to limit the risk of deterioration to residual hearing, the MPL model assumes that the sound exposure resulting from the use of hearing aids should not reach levels that could damage the hearing of individuals without hearing problems. The results of the study demonstrated that the Humes and Bess (1981) hypothesis underestimated the permanent shift actually noted among the population in the study, while the MPL model provided more accurate predictions.

In a second study by Macrae (1991b), predictions were made using the MPL model, but this time in combination with the equations of the ISO 1999 standard (1990) instead of those of Kraak

(1981) to predict the PTS resulting from noise exposure. Two shortfalls in the Kraak (1981) equations motivated this choice, (1) the difficulty of extracting the effect of age, and (2) the impossibility of predicting the distribution of PTS at diverse frequencies. It was therefore concluded that if the prescriptive formulas for gain recommended by Byrne and Dillon (1986) are used, with exposure similar to that reported by Macrae (1991a), a slight PTS is inevitable among hearing aid users with severe to profound sensorineural hearing loss, especially in high frequencies. It also indicated that the model must be verified in the scope of a longitudinal study before being used clinically to determine the risk of aggravation hearing loss.

In 1993, Macrae attempted to predict the quantity of temporary threshold shift in a 15-year-old girl following four hours of exposure at school, by again using the MPL mathematical model in combination with the asymptotic PTS predictions of Mills and his colleagues (Mills et al., 1979). A similar approach to that of the 1991 study was used to establish the actual sound exposure levels. This time, however, a dosimeter worn by the young girl, with the microphone attached to her left collar, made it possible to estimate the input levels of the hearing aid. These input levels, the noise spectrum measured in the 1991a study, as well as the *in situ* etymotic measurements of the real-ear insertion gain (real-ear insertion response) and the input-output function of the device at the volume set were used to establish actual sound exposure levels. The sound levels near the eardrum with amplification of ambient noise by the hearing aid were calculated by adding the sound levels measured with the dosimeter to the gain values obtained during the etymotic measurements. The author mentioned a correction to transform a diffuse field value into an equivalent value measured at the eardrum: that of the temporary shift risk criteria used in the model. Again, it was found that the mathematical model proposed could adequately predict the amount of temporary threshold shift.

By using a similar approach and a dosimeter to record the input levels of the hearing aid, Macrae (1994a) demonstrated the effectiveness of the MPL model in combination with the Mills et al. (1979) equations to predict the quantity of temporary threshold shifts measured among six students and a teacher with severe to profound sensorineural hearing loss, following an approximately four to seven hour exposure. Moreover, the model was used to establish safe asymptotic temporary threshold shift (ATTS) limits according to the degree of hearing loss. In order to avoid an ATTS exceeding those limits, Macrae recommended reducing the gain of hearing aids.

That same year, Macrae (1994b) again used the MPL model, combined with Mills et al. (1979) equations, to predict the quantity of asymptotic temporary shifts associated with hearing aids adjusted according to the prescriptive formulas recommended by the NAL (National Acoustic Laboratories). By comparing the values to the safe limits of ATTS established in the previous study, Macrae was able to demonstrate the effect of and risks entailed in an excessive gain and high input levels of hearing aids on hearing. To make these predictions, the noise dosage established by Macrae in 1993 was used. According to comparisons between the ATTS predicted under various hearing aid use conditions and the established safety limits, it would appear that:

- An ATTS is unlikely for children in whom the pure sound average at 500, 1000 and 2000 Hz does not exceed 60 dB HL, if the hearing aid is adjusted according to the NAL recommendations, for typical average sound levels (below 61 dBA). For more pronounced loss (between 60 and 100 dB HL), the amount of ATTS at safe levels, i.e., that will probably not cause a PTS, is expected. However, for a MSP of over 100 dB HL, the amplification necessary will generate unsafe levels of ATTS and a PTS will then be probable.

- If the insertion gain actually measured is 15 dB higher than that recommended, the ATTS generated in presence of typical average sound levels would be unsafe for an MSP above 80 dB HL.

- Finally, in the presence of excessive gain and high sound levels (approximately 75 dBA), an unsafe ATTS is expected for an MSP equal to or higher than 50 dB HL.

Thus, the recommendation is that hearing aid users who prefer using a higher gain than that recommended in the NAL's prescriptive formulas avoid exposure to loud sound environments.

In 1995, Macrae investigated the possibility of predicting the PTS associated with long-term hearing aid use from the quantity of TTS produced after a day of use. He used data on the permanent threshold shifts of eight children with sensorineural loss, identified in a previous study (Macrae, 1991a), which he compared with ATTS estimated from an MPL model for each of the children, for audiometric frequencies of between 500 and 4000 Hz. The results of this study revealed a good match between the degree of ATTS predicted and the PTS observed at each frequency, with the exception of that of 4000 Hz, at which the ATTS predicted is significantly less than the PTS observed. The conclusion is that it that the eventual permanent deterioration of hearing thresholds associated with hearing aid use could be reasonably estimated from the ATTS observed at the end of the day.

In 1998, Macrae attempted to further validate the mathematical model by comparing the ability of eight different approaches to predict permanent threshold shifts caused by excessive amplification (with the gain used being higher than the recommended gain), among eight children with severe sensorineural loss (data from Macrae, 1991a). These approaches consisted of proposing alternatives for each component of the model (MPL compared to another hypothesis to adjust the prediction for people with sensorineural loss; use of LAeq or LAmn, or the average of levels in the ear in dBA, to describe the sound exposure; whether or not there is a half-octave shift between the frequency of the sound exposure and the frequency at which the threshold deterioration occurred). It was concluded that the most appropriate model is the one that uses the LAmn, the MPL and a frequency shift.

As described in this study, the mathematical model can be described in three stages:

1. Determination of the equivalent continuous sound exposure level during hearing aid use (by using the average of the dBA levels obtained in the ear);

2. Use of the equivalent continuous level to predict the threshold shifts that would occur in a person with normal hearing (by using a half-octave shift between the frequency of exposure and the frequency at which deterioration is assumed in the prediction): Kraak equations (1981);

3. Adjustment of the prediction for a person with sensorineural loss by using the MPL (Humes and Jesteadt, 1991).

Using the model, it appears possible to determine with sufficient accuracy the amount of expected threshold shifts (PTS, TTS or ATTS), and to compare that value with the actual shift observed in order to determine whether amplification by hearing aids contributed to aggravating the loss, or if other factors are in play.

Although Macrae's work dealing with a predictive model of hearing shift appeared promising in the 1990s, we find no trace of this model in recent publications. Its utility appears to be limited to hearing aids with linear amplification, while the model is less applicable to devices with variable gain according to the input level. It is important to note that most hearing aids available on the market and prescribed today are not of the linear type.

C.3 Recommendations Reported Concerning Hearing Aid Use in Noisy Workplaces, Risk of Aggravation to Hearing Loss

Workers with hearing loss can opt to wear hearing aids at work to amplify sound signals that are important for the safe and efficient accomplishment of their tasks. Hearing aid use, however, raises specific concerns about the risk of over-amplification. In order to limit the risk of damaging residual hearing in such a case, the maximum power output (MPO) of the hearing aids could be adjusted and limited. In fact, the following extract from an email received from the representative of a hearing aid manufacturer indicates that although there is not a specific mode designed for hearing aid use in noisy workplaces, the adjustment of the output limit level (MPO) means that the levels generated by the device would be always lower than 85 dB. The representative also added that the active noise reduction algorithms should ensure that a large portion of ambient noise would be suppressed and therefore not amplified.

> *"To my knowledge we do not have functionality specifically aimed at the users you describe. I do however think that some of the functionality we offer in hearing instruments in general will apply to this user group. The convention is that long or repeated exposure to sounds at or above 85 decibels can cause hearing loss. Hearing instruments offer some mechanisms to limit the sound pressure levels being presented to the user from the hearing instrument.*
>
> *One of these is the MPO (maximum power output) limitation. The MPO levels can either be predicted based on the patients audiometric data, or can be setup based on the patient's loudness tolerance data. For a patient who works in noisy surroundings it would be prudent to make a "work" program in the hearing aids with lower MPO settings than are normally set for normal use programs. The MPO could be reduced to 80-85dB in the "work" program, ensuring output levels are not damaging but maintaining audibility of speech.*
>
> *Another function is the noise reduction. Our current top end offering includes environment specific noise reduction settings. This means that the noise reduction algorithm will be more aggressive (make larger downward gain settings) when the environment is more noisy."* [sic]

However, such an approach does not guarantee that workers would not be exposed to potentially dangerous sound levels, because the maximum output of hearing aids, measured in dB SPL, does not directly compare with regulatory limits of sound exposure, which are expressed in dBA. The maximum output of hearing aids is typically regulated according to the individual's discomfort threshold, or on the basis of discomfort thresholds measured with relatively brief sound signals. However, discomfort thresholds measured in a clinic may not be very representative of tolerance over longer durations (for example, an eight-hour work shift) and are often higher than the sound levels that could damage hearing when continued over a long period. In addition, a too restrictive maximum output could get in the way of the clarity of signals and introduce distortion.

Some organizations have issued recommendations concerning hearing aid use in noisy workplaces. In the US, OSHA (2005) acknowledged that hearing aids may amplify sounds at levels that exceed the allowable limits (90 dBA Leq-8 h), but that, in certain cases, they may be used under an earmuff-type protector. Regular monitoring of workers who wear hearing aids is recommended in order to act quickly if changes in hearing are noted. Along the same lines in Canada, Worksafe BC notes that hearing aids can generate dangerous levels of sound for hearing, even when they are equipped with circuits that make it possible to limit loud noises.[5] With respect to the use of hearing aids under earmuffs, the organization states that a class A protector has too much attenuation, while with a class B type protector, the use of a hearing aid may no longer be necessary. A disadvantage noted in the case of this option is perspiration under the earmuffs that could damage the hearing aid. That organization also mentioned that communication headsets could facilitate communication in noisy workplaces for workers with hearing loss.

According to Chartrand (2003), any hearing aid should have a volume control, unless that option is counter-indicated. Among the reasons motivating this recommendation, he states that without volume controls, the user could be exposed to amplified sound levels that could damage residual hearing.

In 2000, Dolan and Maurer discussed the safety and management aspects related to hearing aid use in the workplace and noted that regular assessment of hearing thresholds makes it possible to determine whether a worker is at risk of over-amplification. The following provisional guidelines are set forth for the management of workers who wish to wear hearing aids at work:

- Hearing aids should never be worn in noisy environments characterized by an exposure level above 90 dBA; hearing protectors should be used instead;
- The worker must be registered in a monitoring program, even if the sound levels in the workplace do not exceed the action criteria of 85 dBA established by OSHA;
- The difference noted in hearing thresholds at all the frequencies must be established through an initial reference audiogram; a threshold shift of more than 10 dB could indicate overexposure;
- In the case of threshold shifts of 10 dB or more at 2000, 3000 and 4000 Hz, hearing protectors must be worn;
- Hearing aids that are turned off are not effective hearing protectors;
- Hearing must be evaluated without hearing aids.

The Ordre des orthophonistes et audiologistes du Québec published a practice guide for its members concerning over-amplification and the management of the associated risks (OOAQ, 2000). The document first examined the literature on over-amplification and other possible sources of aggravation of hearing loss. What follows are the main conclusions:

[5] WorkSafe BC. *Hearing Aids at Work*. Found at http://www2.worksafebc.com/pdfs/hearing/hearing_aids_at_work.pdf [Last consulted on July 16, 2015].

- There is a real risk of aggravating hearing loss that manifests itself in a similar way to occupational hearing loss;
- A noise considered harmful for someone with normal hearing is also harmful for someone with hearing loss (limit of maximum exposure in industrial environments = 115 dBA at the opening of the auditory canal; vulnerability to acoustic trauma for sound levels at the opening of the auditory canal of 130 dBA);
- When hearing loss worsens, other exogenous and endogenous causes must be eliminated as potential causes;
- Generally, personalized adjustment of hearing aids using established prescriptive methods is safe for most users.

Guidelines to manage the risk of over-amplification are then suggested. First is a recommendation to adjust the gain and the maximum output of hearing aids according to established prescriptive methods, such as the NAL and the DSL, and to verify afterward whether targets have been reached by measurements close to the eardrum or with a 2cc coupler by using the measured or estimated real-ear-to-coupler-difference (RECD). The document lists sound pressure levels that are potentially harmful near the eardrum, between 250 Hz and 4000 Hz, for an input of 90 SPL. This is the allowable maximum value of 115 dBA at the opening of the auditory canal converted into sound level near the eardrum at each frequency and taking into account the correction factors to transform the dBA into dB SPL, as well as the transfer function of the auditory canal. Similar values for a risk of acoustic trauma based on the allowable maximum value of 130 dB SPL at the opening of the auditory canal are also provided. The guide also provides warnings for conductive, central and severe to profound degrees of loss. For profound degrees of loss, there is recognition that the amplification required to ensure adequate hearing of various acoustic clues entails a risk of damaging residual hearing. Although personalized adjustment of hearing aids using a prescriptive method is important to minimize risk, the nature of the signal to which the individual is exposed and the dose of exposure must also be taken into consideration.

In order to guide professionals in estimating the risk, an evaluation protocol is provided in Appendix 4 of the OOAQ document. Simply put, after adjusting the hearing aids, the professional must first (1) ensure that the values measured close to the eardrum are lower than the maximum values proposed; (2) determine the input level necessary to produce such values; and (3) estimate the actual amplification dose on the basis of daily activities, their duration and their frequency. If there is potential risk of over-amplification, various technical solutions are recommended (compression of the extended dynamic range, devices with multiple memories that enable personalized adjustment in various hearing contexts, directional microphones, noise reduction algorithm, FM system), binaural amplification to reduce the gain required in each hearing aid because of the phenomenon of loudness summation, and environmental options, such as temporarily removing the hearing aids.

Regular monitoring of the user is especially important to identify the over-amplification effect when it occurs. A follow-up evaluation is recommended after one month of new hearing aid use. If hearing remains stable, an adjustment of the devices is not required. If there is a drop in hearing, recovery of thresholds after removing the hearing aids for a period of 24 to 48 hours strongly suggests over-amplification, and new adjustment of the devices (reduction of gain and maximum output) accompanied by follow-up two weeks later is justified. However, if thresholds do not recover, other causes that could explain why the hearing loss is continuing should be investigated through a complete audiological, medical and genetic evaluation. Periodic long-term monitoring is also necessary to see whether or not the hearing thresholds are stable. Users must be informed about the possibility of hearing deterioration, the potential adjustments that they can make to the hearing aids in various use contexts, and the necessity of consulting a hearing professional as soon as a drop in hearing is suspected.

On the basis of the information gathered, there are no clearly established recommendations for workers who wish to or who must wear hearing aids in noisy workplaces. There are recommendations that hearing aids be adjusted according to established prescriptive formulas to limit the risk of further damage. However, appropriate adjustment or verification of hearing aids does not guarantee that hearing will not deteriorate. There is absolutely no doubt that regular clinical monitoring of workers who use one form or another of amplification in the workplace is crucial to determining at an early stage whether their hearing has worsened.

Given this, some workers may consider wearing hearing aids that are turned off in order to protect their residual hearing in noisy environments (Hétu et al., 1992). Although an exhaustive review of the literature was not carried out to explore the effectiveness of such an option, it could be possible that the earmold of the hearing aid would act as a hearing protector and that a made-to-measure device would be more comfortable than the hearing protectors usually provided in the workplace (Chalupka, 2009). In general, the authors feel that this practice does not provide adequate protection and they discourage it (Chalupka, 2009; Dolan and O'Loughlin, 2005), explaining that workers risk exacerbating their hearing loss (Henchi et al., 2008), even at sound levels deemed to be safe (Dolan and O'Loughlin, 2005; Verbsky, 2002). The warning is sometimes relaxed if the earmuff or hearing aid earmold is not vented (Henchi et al., 2008).

However, earmolds were not designed for this purpose and not much is known about how well they could attenuate sound. Any factor that could modify the seal of the earmold in the ear could diminish or negate the attenuation provided, as would the presence of a vent and the use of an open earmold. Workers may also forget to turn off their hearing aids when going from a less noisy environment to a noisy one, or they may turn on their hearing aids at certain times in order to better hear sound signals. In both cases, this could considerably increase sound exposure levels. In the United States, OSHA (2005) clearly states that hearing aids that are turned off cannot replace hearing protectors because they do not sufficiently block sound, but they could attenuate it to the point of impairing workers' ability to detect and recognize it.

Despite the lack of validated tools or protocols available to evaluate the risk of aggravating hearing loss through the use of hearing aids in noisy workplaces, certain approaches have been suggested. Among them are those of the OOAQ (2000), which suggests a risk assessment protocol and makes some recommendations when such a risk is probable (such as technical solutions, binaural amplification and environmental options).

Alternative or additional options to wearing hearing aids should be considered (e.g., wearing hearing protectors with an integrated communication system, hearing aids worn under a hearing protector with uniform frequency sound attenuation) in order to ensure communication and the safety of workers (Preves et al., 1998; Plyler and Klumpp, 2003; Dolan and O'Loughlin, 2005; Ghent, 2014). Again, an exhaustive review of the literature on these alternative or additional options was not carried out.

As indicated previously, with respect to hearing loss, there appears to be a considerable conflict between the need to amplify sound signals in an attempt to re-establish communication and to ensure safety and efficiency at work, and that of protecting residual hearing. To address the needs in these various areas, which are all important, using hearing aids that are turned on under protective earmuffs is an option worth considering. In her doctoral thesis, Verbsky (2002) performed a speech comprehension test in noise among individuals with hearing loss. Those who wore hearing aids underneath earmuffs performed better than when they used hearing protectors only.

In its December 2005 *Safety and Health* newsletter, the US Department of Labor did not reject this practice, but stressed the need for individual assessments to determine whether hearing aids could be worn adequately under protective earmuffs. Chalupka (2009) noted the necessity of developing protocols to properly carry out these individual assessments. He stated that the following elements should be taken into account and monitored: the nature of tasks being performed, communication needs, the work environment (including the evaluation of noise levels), the type of hearing loss, its degree, and the worker's preferences.

In a commercial publication from a hearing aid manufacturer, Ghent (2014) discussed the difficulties experienced by people with hearing loss working in noisy workplaces, as well as the various options possible to protect their residual hearing. He presented a range of options available when hearing aids are programmed (multiple programs, technologies to improve speech perception in noise, the reduction of the Larsen effect), in addition to other technologies that can be used with hearing aids (direct audio input, induction loop, Bluetooth connectivity), and technological progress made in hearing protectors (protectors with uniform frequency attenuation and protective headsets with circuitry). The author encouraged the use of hearing aids in combination with earmuff-type hearing protectors with uniform frequency attenuation or in combination with electronic earmuffs with integrated communication systems. Although he mentioned that the Larsen effect can be a problem when the fitted ear is covered, he noted that most modern hearing aids have an algorithm that can reduce the effect of this acoustic feedback, and that the gain of hearing aids can also be adjusted accordingly. He emphasized that, to get the maximum benefit, workers must also bring their hearing protectors and any other personal protection equipment to their appointment with the audiologist. The article ends with a description of ten different options of use for workers with hearing loss, in terms of the constraints related to communication and hearing protection.

It should be noted that the recommendations provided in the previous paragraphs must be applied with caution, because they are not necessarily founded on evidence. For example, despite the fact that wearing hearing aids under earmuffs could improve some hearing ability while protecting an individual's residual hearing, a reduction in the ability to localize sound remain possible, especially in front/behind positions, because hearing aids and earmuffs can alter the natural clues normally used to localize sounds in the environment.