

HEARING LOSS ANALYSIS IN FULL SCALE ACCIDENT RECONSTRUCTION

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ABSTRACT

Airbags are, together with the three-point belt, the most effective passive safety equipment of vehicles. However, literature shows that sound pressure levels of up to 170 dB can occur during airbag deployment. A literature review revealed no systematic experimental data on possible hearing loss by airbag deployment, that also takes any other crash accompanied noise into account, such as deformation and impact noise. Also the rising number of airbags per vehicle resulting in a higher number of deployed airbags in an accident was not addressed with respect to hearing loss. Thus, an extensive test matrix of noise measurements during airbag deployments was conducted including onboard measuring during crashes and static measurements. Dynamic and static experiments with single and multiple airbag deployments were conducted. The results of this study show, that in the analyzed crash constellations the acoustic emission of the collision as well as the car deformation can trigger the stapedius reflex before the airbag deployment. The stapedius reflex protects the inner ear at least partially in case of dangerous sound levels. However, it seems that multiple airbag deployments in a short sequence pose a considerable risk for hearing impairments despite the fully contracted stapedius muscle. Further and in line with Price et al. (2013) it was found that the risk of hearing loss is lower with closed windows. The analysis of patient and accident data showed no link between airbag deployment and hearing loss. This might be caused by low case numbers of reported hearing loss problems up to now.

In conclusion the results show that a singular analysis of the sound pressure of airbag deployments without crash accompanied noises is not sufficient as the protective effect of the stapedius reflex is neglected. Still, successive airbag deployments in a short timeframe raise the risk of hearing loss. Further investigation on hearing impairment due to airbag deployment and triggering of the stapedius reflex is needed and the data acquisition of accidents and patients should consider hearing loss aspects.

KEY WORDS

Airbag, hearing loss, accident reconstruction, stapedius reflex

INTRODUCTION

Casualties show that hearing loss due to airbag deployment in passenger vehicles can be found in medical records of patients (Saunders et al., 1998). Allen et al. (1971) reported sound pressure levels of airbags of up to 170 dB, which is comparable to a gunshot, these sound pressure levels were verified for example by Price et al (1996) for further airbag generations. An exposure to such high sound pressure levels can induce steady hearing loss, which can lead to social isolation. Yaremchuk et al. (2001) analysed 71 patients with otologic symptoms after airbag deployment and showed that the hearing loss that occurred may have affected one or more frequencies. Based on the pure sound pressure level of airbag deployments, Saunders et al. (1998) estimated a 7000 to 28 000 hearing loss injuries due to airbag deployment between 1988 and 1998, but these number of cases were not reflected in clinical data bases or literature (Saunders et al., 1998).

Therefore, we screened accident and patient data to analyze how many cases can be identified based on actual data acquisition and to see if the problem of linking hearing loss statistically to airbag deployment in accidents can be addressed. Despite the low number of hearing loss due to airbag deployment reported by literature, experiments were conducted to address the high sound pressure levels reported in the literature. Previous studies have often neglected the link between the measured sound pressure levels caused by the airbag and noises accompanying a crash such as structural vehicle deformation and impact noises. For example in Rouhana et al. (1994), Price et al. (1996), Rouhana et al. (1998) and Banglmaier et al. (2003) experiments with deploying airbags were conducted with standing vehicle. Therefore, this study aimed to calculate the risk of hearing loss due to airbag deployment in combination with crash accompanied noise. Several aspects were addressed in these experiments. The influence of single or multiple airbag deployments concerning hearing loss was analyzed to address the increasing number of airbags per vehicle resulting in a higher number of airbag deployments in accidents. A comparison between risk of hearing loss caused by airbag deployment in vehicles with opened and closed windows was conducted, because it is not proven yet if a closed compartment lower the load on the inner ear.

METHODS

Patient and accident data

Within this study in-depth accident data from the German In-Depth Accident Study (GIDAS) (Johannsen et al., 2017) were analyzed using accident data with passenger vehicles with production start in 2001 or later. 2053 driver and 533 passengers were considered for frontal collisions with another passenger vehicle, heavy goods vehicle or an object. 1454 near-side occupants and 1392 far-side occupants were considered for side collisions. These cases were analyzed with respect to hearing related injuries based on the Abbreviated Injury Scale (AIS 2005 Update 2008) wherein a tinnitus is the only codable hearing injury in GIDAS. Patient data was analysed based on expert reports of the German Hearing Centre Hanover that address hearing loss linked to accidents with airbag deployment. Another approach to gain patient data was a direct query of all patients of the German Hearing Centre Hanover between May 2016 and April 2017, if their hearing problem is linked to an airbag deployment.

Accident reconstructions and static airbag deployment experiments

In this study several experiments were conducted to address sound pressure emission of airbags. Two experimental accident reconstructions were conducted twice with different airbag triggering strategies. The first case was a frontal pole impact of a 2008 Seat Leon with 50 km/h colliding speed against a tree with 400 mm diameter and with 95 mm offset. Only the driver airbag was triggered in the experiment by the control unit of the vehicle at 43 ms (the passenger airbag was disconnected). In a variant of this accident reconstruction, the trigger time was set to 20 ms to address the poor chest deflection, all other parameters were set stable. Sound pressure was recorded with two different devices. The NTI Audio Analyzer XL2 with the microphone M4216 was used as an onboard device. This microphone was aligned to the steering wheel centre and attached to the camera stand replacing the passenger seat. The distance between steering wheel centre and microphone was 600 mm. The second sound pressure recorder was a Brüel & Kjaer 2250 with microphone 4189. This external recorder was aligned rectangular to the t_0 -position of the steering wheel centre at the left side of the vehicle with distance 3500 mm and height of 1130 mm, serving as a backup device and for verification purposes. The SAE J247 was not used, because this standard includes only static measurement of acoustic impulses and no acoustical measurements during crash tests.

The second accident reconstruction was a full width rear end collision without offset, where a Fiat 500 (2008) collided with 35 km/h with a standing (hand brake activated) Skoda Fabia (2009) in an under ride situation. The under ride situation was addressed by suspension manipulation so that the lower side of the rear end crossbeam of the Skoda had a ground clearance of 525 mm. The suspension of the Fiat was not manipulated due to minimal ground clearance required by the crash facility of the Technical University of Berlin. The impact speed of 35 km/h was overestimated to ensure an airbag deployment triggered by the control unit of the vehicle. The impact speed of the accident was calculated between 15 and 30 km/h. In a variant of this accident reconstruction the airbag deployment was suppressed, because only marginal airbag interaction was seen for the driver and no airbag interaction was seen for the passenger. The same sound pressure recorders were used similar to the first accident reconstruction. The NTI Audio Analyzer XL2 with microphone M4216 was used as an onboard device. Due to the presence of two dummies in the vehicle the audio analyzer was attached to a mount, that was welded to the outer side of the driver door. The microphone was aligned to the steering wheel centre with a distance of 440 mm. The second sound pressure recorder was a Brüel & Kjaer 2250 with microphone 4189 and positioned similar to the previous accident reconstruction. The two accident cases were chosen based on an analysis of dummy readings addressing suboptimal trigger time in cases with poor structural interaction and unnecessary airbag deployment in accidents with low accident severity to address other work packages of the underlying project. The additional sound pressure measurements were performed parallel.

In order to validate the sound pressure recordings of the accident reconstructions, static analyses of airbag deployments were performed using the same vehicles with the same sound pressure recordings. Additionally, another Brüel & Kjaer sound pressure recorder with five high pressure microphones was used to double the previous microphone positions as a reference and to add other interesting positions inside the vehicle such as headrest of the driver and rear centre seat with direct view to the driver airbag. All microphone positions are shown in Figure 1. The test matrix of the static sound pressure analysis of deploying airbags included experiments to compare the static experiments with the measurements from the accident reconstructions (Seat Leon: driver airbag, Fiat 500: driver airbag, passenger airbag and driver's knee airbag) in order to assess the

influence of the crash accompanied noises such as deformation and impact noises. The driver, passenger, side and curtain airbag of the Seat Leon and the side and curtain airbag of the Fiat 500 were additionally analyzed to address their sound pressure separately and to investigate, if the risk of a hearing impairment is higher for a vehicle with closed or open windows.

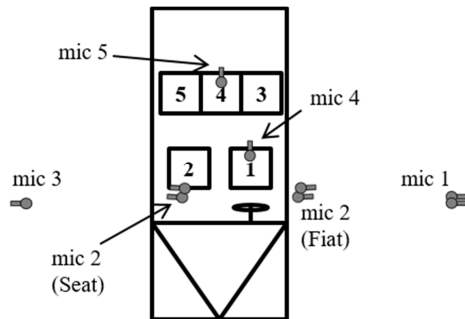


Figure 1: Microphone positions for all experiments, doubled microphones only used for the accident reconstructions

The recorded data were analyzed using the Auditory Hazard Assessment Algorithm for Humans (AHA AH) model that indicates the risk of a Compound Threshold Shift (CTS). A CTS is a reduction in hearing sensitivity due to the combined influence of temporary threshold shift (TTS) and permanent threshold shift (PTS). While a temporary shift recovers over time, the PTS remains as a chronic hearing loss. The AHA AH model was developed in the 80s by Price et al. (1986) and the recordings were analyzed using the version 2.1 from 2013 (Price et al., 2013). The model calculates the risk of a CTS due to blast events such as gunshots or airbag deployments. The AHA AH algorithm models the propagation of sound and blast waves in a free field situation and the transmission in the middle and inner ear. The high nonlinear behavior of the middle ear at high sound pressure levels is implemented in the model. In the analysis of sound pressure levels above 130 dB this nonlinear behavior needs to be considered to avoid overestimation (Price et al., 2013). The AHA AH model also includes the frequency dependent behavior of the 23 segments of the basilar membrane resulting in a calculated segmental deflection of the basilar membrane named Auditory Risk Unit (ARU). A higher deflection leads to a higher risk of damaging the basilar membrane. Experiments with cats, chinchillas and data from voluntary test persons from the 60s and 70s showed a correlation of 0.94 between the CTS and the ARU value following the empiric equation 1 (Price et al., 2013).

$$CTS = 26.6 * \ln(ARU) - 140.1 \quad (\text{Eq. 1})$$

Price et al. (1986) determined a threshold value of 25 dB CTS measured directly after the blast event to expect PTS in humans. This careful assumption corresponds to clinical observations, but due to lack of sufficient data and highly individual behavior the relationship between CTS and PTS could not yet be statistically captured. For example, Liberman et al. (1982) showed in animal studies that a CTS of up to a maximum of 40 dB can fully recover in selected cases, demonstrating the absolute upper limit for a full recovery of hearing thresholds. Regarding the 25 dB CTS by Price et al. (1986) an ARU value of 500 and for the 40 dB CTS by Liberman et al. (1982), an ARU value of 868 is calculated as a limit for obtaining a PTS. In essence, it can be assumed that an ARU value higher than 500 indicates a possible PTS and an ARU value of 868 indicates a definite occurrence of a PTS. A complete risk curve for PTS in dependency of CTS would be highly desirable, but due to the lack of sufficient data and highly individual behavior this is not possible at the current stage. For the analysis of potential hearing loss in our experiments, we will use an ARU value of 500 as the threshold.

The AHAAH model considers two conditions of a test person: warned and unwarned ear condition. Price et al. (2013) elaborated that the risk of hearing loss due to a blast might be affected by the awareness of this upcoming blast event. This effect can be caused by the conditional triggering of the stapedius reflex. While the triggering of the stapedius reflex at sound pressure levels of 90 dB (pure tones) and 80 dB (broadband noise) is non-controversial, the conditional triggering of the stapedius reflex has not yet been proven conclusively. Nevertheless, both conditions are provided by the AHAAH model and will be both applied on our recorded data.

RESULTS

Patient and accident data

The analysis of GIDAS showed that in eight cases with frontal impact and in seven cases with side impact a tinnitus was coded. In a database query on all patients of the German Hearing Centre Hanover between May 2016 and April 2017, two patients linked their hearing problem to an airbag deployment. The analysis of 103 medical reports of the German Hearing Centre at MHH that investigated a potential causality between a hearing loss and an accident with airbag deployment did only reveal a single case where a link between airbag deployment and hearing loss could be demonstrated. These low occurrences correspond to other studies that also found a low number of clinical cases with airbag indicated hearing loss, e.g. Saunders et al. (1998), Traynor (2012) and McFeely et al. (1999).

Accident reconstructions and static airbag deployment experiments

In the first accident reconstruction sound pressure levels up to 134 dB of deformation noise at 18 ms after t_0 were measured which made triggering of the stapedius reflex possible. At 43 ms the airbag deployed and the sound pressure level reaches 160 dB, this maximum value happens in the rising phase of the stapedius muscle, which needs approximately 35 ms to take effect. Nevertheless an ARU value of 276.0 was calculated with the AHAAH in the unwarned condition. In warned condition an ARU value of 256.9 was calculated. In the same accident reconstruction with earlier airbag trigger time (20 ms) an ARU value in the unwarned condition of 452.6 and in the warned condition of 364.0 were calculated. Based on this recording the crash accompanied noises before the airbag deployment were eliminated in the sound file to address a trigger time of 3 ms of the airbag. An ARU value of 615.0 was calculated for this manipulated recording. This shows that the earlier the airbag deploys in the rising phase of the stapedius reflex the higher is the calculated ARU value. As the ARU values with crash accompanied noises were below 500 and therefore of low risk for PTS, the isolated airbag deployment noise indicates a possibility of a PTS. In the second accident reconstruction three airbags deployed: Driver, passenger and driver's knee airbag. The deformation noises lead to sound pressure levels up to 134 dB at 12 ms after t_0 so that the stapedius reflex could be triggered. The first airbag deploys at 67 ms, so that the stapedius reflex is fully developed, however in both conditions an ARU value of 714.4 were calculated for this accident reconstruction. For comparable results the passenger and knee airbag were removed from the audio file and an ARU value of 366.1 was calculated. This shows that the short sequence of airbag deployments (three airbags within 10 ms) can cause a PTS despite the triggered stapedius reflex. In the variant of this accident reconstruction without any airbag deployments an ARU value of 5.3 was calculated, so that the risk of a PTS is very low. With the results of this accident reconstruction with the Fiat, a telephone interview with the driver of the accident vehicle was conducted. The driver confirmed that a tinnitus occurred for one month after the accident, but the tinnitus was not reported to GIDAS and therefore not coded in the GIDAS data. An ear screening to proof if a PTS occurred

was not performed, but it could be assumed that a C5-dip appeared, which does not affect the subjective hearing of the patient, but speeds up presbycusia.

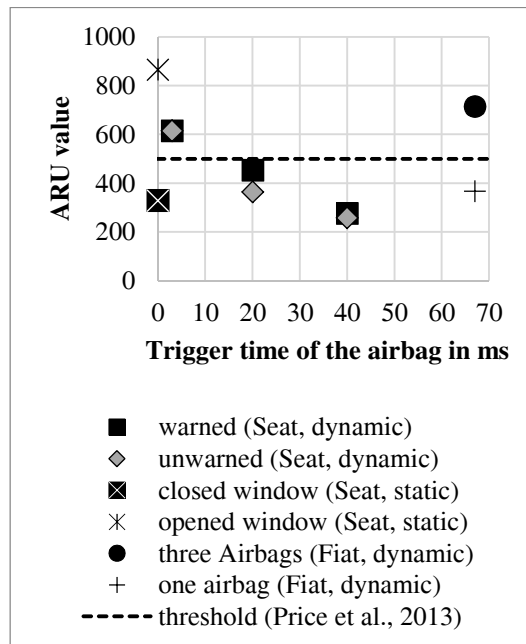


Figure 2: ARU values of the analyzed accident reconstructions (dynamic) and static experiments (airbag deployment in standing vehicle) with respect to the recommended threshold by Price et al. (2013) of 500 ARU

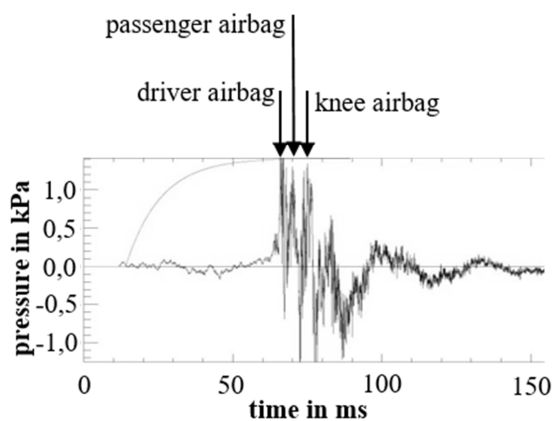


Figure 3: sound pressure graph for the accident reconstruction with Fiat 500, the three airbag deployment events are highlighted resulting in an ARU value of 714.4

The results of the static experiments are based on the recordings of the NTI XL2. The other recordings confirmed the measurements relative to the driver's ear. For example for the deployment of the driver airbag of the Seat Leon a sound pressure of 160 dB was calculated for the driver's ear based on the NTI XL2. The microphone 5 (Figure 1) measured 148 dB in a distance of 1 660 mm, so that both values can be calculated into each other with a failure of 0.36 dB based on the distance law, which describes a drop of 6 dB of sound pressure level per doubling distance. These measurements show that the use of the distance law inside the vehicle is applicable, but direct view between sender and receiver is required. For the driver airbag of the Seat Leon an ARU value of 865.2 was calculated showing a high risk of a PTS, while in the corresponding accident reconstruction an ARU value of 452.6 was calculated in the worst case with a low risk of a PTS. This shows that the stapedius reflex with its protective effect to prevent hearing loss can be triggered by crash accompanied

noises such as deformation noises. A singular analysis of the sound pressure of an airbag addressing the risk of a PTS is not recommended and the crash accompanied noises should be considered.

Comparing the sound pressure from the driver airbag of the Seat Leon with open and closed window, the ARU values for the opened window of 865.2 and 328.8 for the closed window were calculated. The lower value for the closed window is probably based on the static air pressure increase in the vehicle compartment. This forced the eardrum in a position of strong tension and the sound transmission to the inner ear is restricted, comparable to the function of the stapedius reflex.

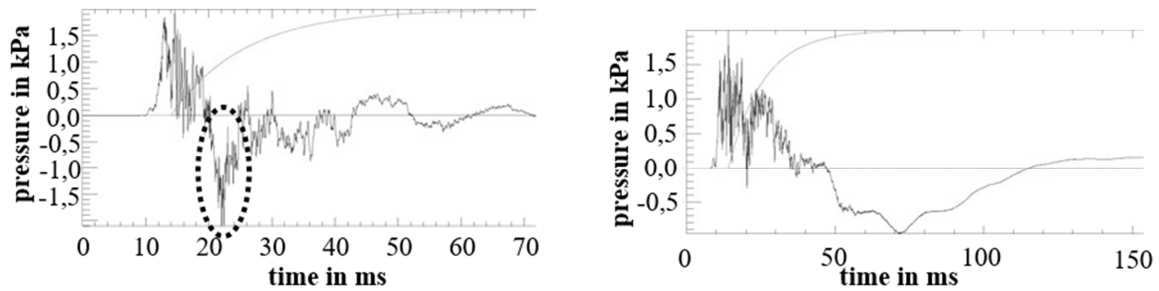


Figure 4: sound pressure graphs for experiment with open (left) and closed (right) window. The negative excursion is highlighted and occur only for open windows

DISCUSSION

The analysis of patient and accident data showed only a low number of cases. It needs to be investigated whether this is actually based on a low number of cases or if hearing loss is not sufficiently covered by data collections. Several aspects affect the data collection of hearing loss. For example, the patient does not notice a hearing loss immediately because only higher frequencies are affected, that can only be seen in a frequency band. Secondly a hearing loss injury steps in the background of the patient, because other injuries are more obvious or relevant to the patient or thirdly a patient recognizes a hearing loss but did not link it to an airbag deployment. The third point can be addressed by awareness, but the first two points needs to be addressed with audiometry. With more extensive data collections the link between airbag deployment and hearing loss can be assessed statistically.

The accident reconstructions and static experiments were conducted with a limited number of experiments, vehicles and airbags. Continuitive accident reconstructions of other constellations needs to be conducted to support the findings of this study for example full width impact or side collisions. Especially side impacts seem to be interesting, because of the short period of deformation noise before the airbag deployment interferes with the rising phase of the stapedius reflex. Also the selection of vehicles needs to be extended to suspend that the measurements are artefacts of the analyzed vehicles and their acoustical behavior. A continuous on-board recording of sound pressure should be applied to crash tests to collect data for different vehicles and impact conditions. The findings of the comparison of closed and opened windows neglect the accompanied crash noises. Considering the crash noise the ARU value decreases from 865.2 (static experiment with open window) to 452.6 for the case with open window and airbag deployment 20 ms after t_0 (dynamic experiment).

A limitation of this study is that hearing is an individual sense organ that reacts different in every human. So that a complete risk curve for PTS in dependency of CTS is not available at the current stage. For example, there exist so called vulnerable ears that are more sensitive to noise exposure. Ernst et al. (1997) report that 5 to 10 % of the population could be affected by such sensitive hearing. This corresponds to findings by Pfander (1975).

Also the stapedius reflex cannot be triggered in every human. Due to neurologic or anatomical abnormality the stapedius reflex cannot be triggered and the inner ear is unprotected against high levels of sound pressure.

Main limitation of this study is the use of the AHAH model, which is well-established in analysis of gunshots and also in use for automotive analysis since 2003 (Price et al. 2013), but the interpretation of the ARU values and their correlation to PTS and CTS is limited. Only for two values (500 by Price et al. (1986) and 868 by Liberman et al. (1982)) the indication of a PTS is classified, so that the assessment of results close to the two values and in between both values is limited. An approach using injury risk curves for PTS should be a part for future scientific research.

CONCLUSION

In conclusion it was shown that cases with hearing loss after airbag deployment occur in a few cases of patient and accident data. In order to link airbag deployment and hearing loss statistically an extensive data acquisition concerning hearing loss in accidents is needed. The conducted accident reconstructions and the analysis of the sound pressure levels with an on-board microphone showed that sound pressure levels up to 160 dB can occur calculated for the driver's ear. Due to the protective effect of the stapedius reflex, which can be triggered by deformation and impact noise, the risk of a PTS is low for a single airbag deployment. In multiple airbag deployments it was shown that the risk of a PTS is higher due to short sequence of blast events. Due to the increase of the number of airbags per vehicle and higher number of airbag deployments in accidents the number of hearing loss needs to be monitored carefully. Further it was shown, that the risk of a PTS is lower if the windows of the vehicle are closed, due to the air pressure increase inside the vehicle.

For further investigations it should be noticed that measuring the sound pressure of airbags with respect to a risk of a PTS the crash accompanied noises should be considered in the analysis to address the influence of the stapedius reflex. In case of direct view between sender and receiver the distance law is applicable. As recommendation, the sound pressure of airbags should be lowered and unnecessary airbag deployment needs to be avoided. Additionally, the collection of injury data of accidents should address hearing loss to link such injuries to airbag deployment events.

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REFERENCES

Allen, C.H., Bruce, R.D., Dietrich, C.W., Pearsons, K.S., (1971): „Noise and inflatable restraint systems: final report”, Cambridge, Massachusetts: Bolt, Beranek, and Newman

Banglmaier, R.F., Rouhana, S.W. (2003): "Investigation into the noise associated with air bag deployment: Part III – Sound pressure level and auditory risk as function of inflatable device", 47th annual proceedings of association for the advancement of automotive medicine

Ernst, A., Lenarz, T., (1997): "Otoacoustic emissions in predicting noise induced hearing loss in vulnerable inner ears", European commission concerted action – protection against noise. University College London

Johannsen, H., Krettek, C., Hannawald, L., Schaser, K.D. (2017): "Consideration of Accident Avoidance Technology within GIDAS". 25th ESV Conference, Detroit, 2017

Lieberman, M.C., Mulroy, M.J., (1982). "Acute and chronic effects of acoustic trauma: Cochlear pathology and auditory nerve patho-physiology." In: *New Perspectives on Noise-Induced Hearing Loss*, pp. 105-135. New York.

McFeely, W.J. Jr, Bojrab, D.I., Davis, K.G., Hegyi, D.F., (1999): „Otologic injuries caused by airbag deployment”, *Otolaryngology – Head and Neck Surgery*, 121(4): 367-73

Pfander, F., (1975): „Das Knalltrauma“, Heidelberg, Springer Verlag, 1975

Price, G.R., Kalb, J.T., (1986): „Mathematical model of the effect of limited stapes displacement on hazard from intense sounds”, *J. Acoustical Society of America*, Supplement 1, Vol. 80

Price, G.R., Rouhana, S.W., Kalb, J.T., (1996): "Hearing hazard from the noise of air bag deployment" *The Journal of the Acoustical Society of America* 99, 2464 (1996)

Price, G.R., Kalb, J.T., (2013): „Using the Auditory Hazard Assessment Algorithm (AHAHAH)", <http://www.arl.army.mil/ARL-Directorates/HRED/AHAHAH>

Rouhana, S.W., Webb, S.R., Wooley R.G., McCleary, J.D., Wood, F.D., Salva, D.B. (1994): "Investigation into the noise associated with air bag deployment: Part I – Measurement technique and parameter study" *SAE Transactions*, Vol. 103, Section 6: *JOURNAL OF PASSENGER CARS* (1994), pp. 1752-1773

Rouhana, S.W., Webb, S.R., Dunn, V.C. (1998): "Investigation into the noise associated with air bag deployment: Part II – Injury risk study using a mathematical model of the human ear" *42nd Stapp Car Crash Conference Proceedings*, Tempe, Arizona, November 2-4, 1998

Saunders J.E., Slattery, W.H., Lux-Ford, W.M., (1998): "Automobile airbag impulse noise: otologic symptoms in six patients", *Otolaryngology – Head and Neck Surgery*, 118(2):228-34

Traynor, R., (2012): "The Effect of Automobile Air Bag Deployment on Hearing", <http://hearinghealthmatters.org/hearinginternational/2012/the-international-threat-of-air-bags/>, accessed September 28, 2018

Yaremchuk, K., Dobie, R.A. (2001): "Otologic Injuries from Airbag Deployment" *Otolaryngology – Head and Neck Surgery*, 125(3):130-34