High-Speed Video Observation of Tympanic Membrane Rupture in Guinea Pigs*

Takuji KOIKE**, Hiroshi WADA***, Fumiaki ITO***,
Kazuyoshi TAKAYAMA**** and Toshimitsu KOBAYASHI†

In this study, the tympanic membrane (TM) of the guinea pig was exposed to a blast wave generated by micro-explosion of 10 mg silver azide, and the time history of TM rupture was recorded using a high-speed video camera. The relationship between the process of TM rupture and the peak pressure of the blast wave was then examined. The critical value which caused the TM rupture was found to be 192 dB SPL (79.6 kPa), and when this level of pressure was applied to the TM, tears were immediately caused in the radial direction, although they did not subsequently expand. When pressures above 195 dB SPL (112 kPa) were applied to the TM, it suffered a perforation, and this perforation continued to expand for several milliseconds, even after disappearance of the pressure change caused by the blast wave.

Key Words: Tympanic Membrane, Rupture, Blast Wave, High-Speed Video, Guinea Pig

1. Introduction

The tympanic membrane (TM) is a conical shaped disk, the diameter and thickness of which are approximately 9 mm and 0.1 mm, respectively. The TM consists of collagen fibers, elastic fibers and fibroblasts, and these fibers mainly run in radial and circular directions. Sounds, i.e., compression waves in air, are converted to mechanical vibrations at the TM. However, overpressure in the ear canal results in injuries to the auditory system, e.g., TM rupture, dislocation or fracture of the ossicular chain and destruction of the sensory structures on the basilar membrane^{(1),(2)}. If the TM were very tenacious and only ruptured due to greatly excessive pressure, sud-

den unphysiological overpressure would cause a direct transmission of the energy of the pressure wave to the ossicular chain and the cochlea. This might cause serious problems such as luxation of the ossicles, rupture of the round window, etc. In actual fact, the TM is a fragile membrane. Rupture of the TM results in a benign lesion and spontaneous healing occurs in 80–90% of such ruptures if the size is small. Therefore, TM rupture can be regarded as a suitable protective mechanism of the ear.

The shape and location of such ruptures have been examined in humans using static pressure⁽³⁾. The static pressure which was found to cause TM rupture in normal ears ranged from 4.9–20.6 kPa, and the ruptures were typically minor tears. Sixty-three percent of the ruptures were located at the anterior part of the TM.

Tympanic membrane rupture in humans and animals in relation to various pressure-time patterns of blast waves has been also reported^{(1),(4)–(6)}. Richmond et al.⁽⁴⁾ reviewed the data on the response of the tympanic membrane to several patterns of pressure-time variations, i.e., smooth-rising waves produced by an apparatus, which applied overpressure statically to the ear canal, complex patterns occurring inside structures, and fast-rising blast waves generated by explo-

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** Department of Mechanical Engineering and Intelligent Systems, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan. E-mail: koike@mce.uec.ac.jp

*** Department of Mechanical Engineering, Tohoku University, Sendai, Japan

**** Shock Wave Research Center, Tohoku University, Sendai, Japan

† Department of Otolaryngology, Tohoku University School of Medicine, Sendai, Japan

sions and shock waves in shock tubes. The highest peak pressure of smooth-rising waves which caused TM rupture in dogs was 203.4 dB SPL (296 kPa). For complex waves occurring inside open shelters subjected to nuclear blasts, the pressure which caused TM rupture in dogs was 200.2 dB SPL (205 kPa), while it was 191.8 dB SPL (77.8 kPa) for fast-rising shock waves in a shock tube⁽⁷⁾. A tendency for the peak pressure of fast-rising pressures to be lower than those for both smooth-rising and complex waves has also been obtained in other animals⁽⁴⁾. Although the location and shape of TM rupture and the peak pressure which causes TM rupture have been reported, as mentioned above, the process of TM rupture due to dynamic pressure has not been observed.

In this study, the TM rupture in guinea pig caused by a blast wave was visualized by using a high-speed video camera. The relationship between the rupture process and the peak pressure of the blast wave was then examined.

2. Methods and Materials

A block diagram of the system for measurement of the process of TM rupture is shown in Fig. 1. This system consists of a pulse generator (NF, FG-121), a retarder (SUGAWARA, RE-306), a laser detonating device (OPTRON, DSM), a pressure transducer (KISTLER, 6215; rise time, 1 μ s), a high-speed video camera (PHOTRON, FASTCAM-Ultima-40 K) and a digital video recorder (SONY, DCR-PC110). An

Fig. 1 Block diagram of the measurement system. An explosive was located at the midpoint between the TM fixed to a holder and a pressure transducer. As a spherical blast wave was generated by a detonation, the change of the pressure detected by the transducer was assumed to be equal to that in front of the TM.

explosive (Silver azide pellet; AgN_3 , 10 mg) was located at the midpoint between the TM and a pressure transducer and detonated by irradiation of a Q-switched YAG laser beam. The TM was hence exposed to a blast wave generated by the explosive. As the distance between the explosive and the TM was equal to that between the explosive and the pressure transducer, the value detected by the pressure transducer was assumed to be the same as that loading the TM. Figure 2 shows examples of pressure-time histories of the blast waves. The shape of the blast wave showed pressure variation accompanying abrupt pressure increase. The pressure then gradually decreased and showed negative value. This pressure variation lasted for approximately 0.2 ms. The peak value of the pressure was controlled by adjusting the distance between the explosive and the TM. The general shape of the blast wave did not vary remarkably even if the distance was changed. As the adjustable range of the distance was limited by the device layout of our measurement system, the peak pressures were varied ranging from 188 dB SPL to 206 dB SPL, depending on the distance between 90 mm and 40 mm.

The laser detonating device and video system were synchronized by combination of the pulse generator and the retarder, and the time recording was commenced at the moment of the detonation. The TM rupture was sequentially monitored with the high-speed video camera at 13 500 frame/sec, and the images were stored in the digital video recorder. The

Fig. 2 Examples of pressure-time history of blast waves. (a) The distance d between the explosive and the TM is 60 mm. (b) $d=90$ mm. Fast-rising waves with short-duration were obtained. The peak value of the pressure was controlled by adjusting d .

TM was sprayed with saline at intervals of 10 minutes to prevent dryness.

Thirteen guinea pigs (25 ears) weighing between 230 g and 375 g were examined. They were anesthetized with diethyl ether and decapitated. Then, the temporal bones were removed and drilled with a rooter (PROXXON, mini rooter) from the side of the external ear canal to expose the whole TM. This temporal bone was embedded in clay and firmly fixed to a holder. The care and use of the animals in this study were approved by the Institutional Animal Care and Use Committee of Tohoku University School of Medicine.

3. Results

An example of the process of rupture is shown in Fig. 3. Although the moment of the TM rupture could not be observed because the saline which was sprayed onto the TM splashed and significantly deteriorated the high-speed video camera images, the TM developed a tear in its radial direction within several hundred microseconds after the blast wave arrived at the TM. However, the tear did not subsequently expand.

Figure 4 shows an example of another process of rupture. Firstly, the TM suffered a perforation in the portion between the manubrium and the tympanic

ring, and the area of the perforation expanded with time even after disappearance of the pressure change caused by the blast wave.

Figure 5 shows examples of images of the TMs after exposure. These results can be classified into 5 groups according to the process of the TM rupture as summarized in Fig. 6. The definition of each group is as follows:

Group 1: The TM vibrated but showed no macroscopic change due to the exposure (Fig. 6 (a)).

Group 2: A tear in the radial direction of the TM resulted from exposure, but this tear did not subsequently expand (Fig. 6 (b)).

Group 3: Some tears occurred in the radial directions of the TM immediately after the exposure. The TM was divided into several parts, but these tears did not subsequently expand (Fig. 6 (c)).

Fig. 3 Example of a process of rupturing. (a) Pressure-time history of the blast wave. The horizontal axis represents the time after the detonation. The position of the arrows shows the time when the following images were taken. (b) Images of the TM at each point of time after an explosive was detonated by YAG laser. 1, $T=0.0$ when an explosive was detonated by YAG laser. 2, $T=0.74$. A tear was caused in the radial direction of the TM. The arrows show the direction of development of the tear. 3, $T=7.40$

Fig. 4 Another example of the process of rupturing. (a) Pressure-time history of the blast wave. The horizontal axis represents the time after the detonation. The position of the arrows shows the time when each image was taken. (b) Images taken at each point of time

Fig. 5 Example of images after exposure viewed from the side of the external auditory meatus. To facilitate comparison of the position of the rupture in each case, the images of the left ear are reversed so that their anterior faces right. Numbers represent each animal.

Fig. 6 Classification of the process of the TM rupture. The areas colored black show the ruptured areas, and the arrows indicate the direction of development of a rupture. The definition of the classification is given in the text.

Group 4: A rupture was generated in the area between the manubrium and the tympanic ring, and the area of perforation expanded with time (Fig. 6(d)).

Group 5: The TM suffered perforation and almost all the parts of the TM were instantaneously blown away (Fig. 6(e)).

Table 1 shows the measured peak pressure of the blast wave and ratio of the ruptured area to the area of the TM for all the animals classified by their respective groups, and distribution of the peak pressure in each group is shown in Fig. 7. The averages of the peak pressure in groups 1, 2 and 3 were 192.7, 192.0 and 191.7 dB SPL (89.7, 83.4 and 78.2 kPa), respective-

Table 1 Peak pressure and ratio of ruptured area

Animal No.	Peak pressure in dB SPL	Ratio of ruptured area (%)
Group 1		
1502R	194.6	0.0
1702R	195.4	0.0
1902R	194.2	0.0
3001L	190.0	0.0
3002R	189.2	0.0
Average	192.7	
S.D.	2.9	
Group 2		
1602L	194.5	2.9
2402L*	194.5	1.2
2502R	188.8	1.4
2902R	190.4	1.2
Average	192.0	
S.D.	2.9	
Group 3[†]		
2303R*	193.8	---
2404L	191.3	---
2501L	190.0	---
Average	191.7	
S.D.	1.9	
Group 4		
1501L	200.0	32.1
1701L	195.7	63.1
1603R	194.6	36.8
2202R	200.3	6.2
2403R	193.3	21.7
3003L	193.0	62.1
3004R	192.8	48.5
Average	195.6	
S.D.	3.2	
Group 5		
1903L*	205.3	100.0
2201L*	199.5	100.0
2301L*	199.9	100.0
2302R*	196.6	99.8
2304R	195.6	100.0
2401R	194.8	93.3
Average	198.6	
S.D.	3.9	

R: right ear, L: left ear

* Malleus fracture occurred.

[†] In group 3, the ratio of the ruptured area could not be determined because the TM was divided into several parts.

ly, and the differences between them were not statistically significant. The average peak pressure in group 4 was 195.6 dB SPL (129.4 kPa), and pressure difference between group 4 and each of groups 1, 2 or 3 was statistically significant (significance level, $p < 0.05$). Although the difference was not statistically significant, the average pressure in group 5 (198.6 dB SPL, 186.7 kPa) was greater than that in group 4. The ratio of the ruptured area to the area of the TM in group 2 was on the order of several percentage points. The ratio in group 4 was far greater than that in group 2, and the area of perforation extended to

Fig. 7 Peak pressure of the blast wave classified according to the process of TM rupture. Pressure difference between group 4 and each of groups 1, 2 or 3 was significant ($p < 0.05$).

more than half of the area of the TM in two cases in group 4.

Malleus fracture was found in groups 2, 3 and 5, and it occurred with high frequency (4 cases out of 6 ears) in group 5.

4. Discussion

4.1 Shape and location of TM rupture

In groups 2 and 3, the TM tore in the radial direction. Although the TM has fibers which run in several directions⁽⁸⁾⁻⁽¹¹⁾, the principal fibers are radial and circular fibers. These two types of fibers are denser and thicker than the other types of fibers⁽¹²⁾, so they are responsible for the tensile strength of the TM. The tensile test using guinea pig TMs showed that the tensile strength in the direction parallel to the radial fiber is 8.8 times stronger than that in the perpendicular direction⁽¹³⁾. Assuming that the TM is semispherically deformed when it is exposed to a blast wave, the stress in both directions becomes equal. In this case, the TM tears more easily in the direction parallel to the radial fibers than in the direction perpendicular to them, because there is a difference in tensile strength according to the direction as mentioned above. For this reason, it is considered that the TM ruptured along the radial fibers as it did in groups 2 and 3.

Stuhmiller⁽¹⁴⁾ reported that a concentration of stress occurred at the tip of the manubrium and along the tympanic ring based on the results obtained by using a finite-element TM model. The density of fibers included in these portions of the TM are higher than that in other portions, and the thickness of the TM in these portions is also great^{(12),(15),(16)}. As shown in group 4, the rupture actually started from the portion between the manubrium and the tympanic

ring and expanded in this area instead of in the part where stress concentration occurred. Therefore, the characteristic structure of the TM, i.e., the thickness and density of its fibers, is considered to be optimized so that the TM in the areas where the concentration of stress occurs is resistant to rupture.

Jensen et al.⁽³⁾ reported that 63% of the ruptures they examined were located in the anterior part of the TM (the right side of the TM when a right ear is observed from the external ear canal in upright position, and vice versa) in human. However, in our observation, the rupture occurred at various locations. Yamamoto et al.⁽¹³⁾ reported that although the tensile strength in the direction parallel to the radial fibers in the posterior part was greater than that in the anterior part in guinea pig, there was no difference in tensile strength in the direction perpendicular to the radial fibers. Rupture of the TM is considered to be strongly influenced by the tensile strength in the direction perpendicular to the radial fibers, which is lower than that in the direction parallel to the radial fibers. Therefore, there may be no tendency for the TM to rupture at a specific location.

4.2 Relationship between the process of TM rupture and the peak pressure of blast waves

No significant difference was found between the peak pressure when the TM did not rupture (group 1) and that when it tore (groups 2 and 3). Therefore, it is considered that the occurrence or non-occurrence of rupturing when the TM is exposed to a blast wave with a peak pressure between 190 and 195 dB SPL depends on individual differences. By contrast, there was a significant statistical difference between the peak pressure in group 4 (195.6 dB SPL, 120.5 kPa) and that in group 2 (192.0 dB SPL, 79.6 kPa) or 3 (191.7 dB SPL, 76.9 kPa), suggesting that the peak pressure which causes perforations is greater than that which causes tears. Based on our results, it can be said that tears occur when the peak pressure is approximately 192 dB SPL (79.6 kPa) and that perforations occur when it is 195 dB SPL (112 kPa) or more. These values are greater than the peak pressure which causes TM rupture in guinea pigs reported by Hirsch⁽⁶⁾ (188.1 dB SPL, 50.8 kPa) and are lower than the value in humans (198.0 dB SPL, 158.9 kPa)⁽⁵⁾ and that in monkeys (198.7 dB SPL, 172.2 kPa)⁽⁶⁾. However, comparison between the absolute values of the peak pressure may be meaningless because they vary depending on the existence of the external auditory meatus (EAM) and shape of pressure wave applied to the TM. Hirsch⁽⁶⁾ performed experiments in guinea pigs under the condition that the EAM was intact. By contrast, in our experiments, the EAM was removed to record the time history of the TM rupture.

Richmond et al.⁽⁴⁾ reported that the blast wave entering the EAM of the human was intensified more than twofold at the TM. Therefore, the removal of the EAM may have some influence on TM rupture.

Concerning the shape of the pressure wave, it has been reported that a fast-rising wave more easily causes TM rupture than a smooth-rising wave⁽⁴⁾ and that the rupture pressure is lower in case of a long-duration wave than a short-duration wave when the duration time is shorter than approximately 5 ms⁽⁴⁾. In our experiments, the effects of the pressure wave on TM rupture were not examined because an explosive was used to generate the blast wave and it was difficult to change its wave shape.

In group 4, the perforation continued to expand for several milliseconds, even after disappearance of the pressure change due to the blast wave. As the distance between the TM and the wall of the tympanic cavity facing the TM was less than 5 mm, it took only several dozen microseconds till the blast wave reflected on the wall of the tympanic cavity arrived at the TM. Therefore, it is quite unlikely that this expansion of the perforation was caused by the reflected blast wave. Richmond et al.⁽⁴⁾ reported that the pressure which caused TM rupture dropped when the TM was exposed to the blasts repeatedly. This means that the TM is weakened by the blasts even if macroscopic changes are not observed. Therefore, the mechanism of the rupture in group 4 can be considered as follows: (1) The strength of the fibers of the TM is weakened when the blast wave strikes the TM directly. (2) The TM vibration resulting from the impulse of the blast wave on the TM continues several milliseconds, even after disappearance of the pressure change due to the blast wave. (3) The destruction of the TM progresses with its free vibration in the portion where the fibers are sparse and the TM is thin. By contrast, in group 2, the fiber strength is not extremely weakened even if the blast wave strikes the TM because the average peak pressure was lower than that in group 4. In addition, individual differences in density of the fiber and in thickness of the fiber layer probably affect the process of the TM rupture.

5. Conclusions

The time history of TM rupture in the guinea pig caused by a blast wave was recorded using a high-speed video system. The process of the TM rupture could be classified into 5 groups, i.e., (1) the TM showed no macroscopic change, (2) a tear in radial direction of the TM resulted, but it did not subsequently expand, (3) some tears occurred in the radial directions, but they did not subsequently expand, (4)

a perforation was generated in the area between the manubrium and the tympanic ring, its area expanding with time, and (5) almost all of the TM was instantaneously blown away. Regarding the peak pressure of the blast wave, a difference between these groups was found. When pressure of 192 dB SPL (79.6 kPa), which was the borderline value which caused TM rupture, was applied to the TM, tears immediately developed in the radial direction of the TM, but they did not subsequently expand as they did in groups 2 and 3. By contrast, when a pressure somewhat above 195 dB SPL (112 kPa) was applied to the TM, the TM suffered a perforation, and vibration of the TM caused the area of the perforation to expand for several milliseconds, even after disappearance of the pressure change due to the blast wave. This was the case in group 4.

In this study, the TM is not in physiological conditions. Removal of the temporal bone and the subsequent removal of the external ear canal may affect the pressure wave characteristics. However, it is clearly shown that the process of the TM rupture varies according to the pressure just in front of the TM. These results will contribute to further study of occurrence and prevention of TM rupture.

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