Mechanical Properties of a Human Eardrum at High Strain Rates After Exposure to Blast Waves

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Abstract The mechanical properties of a human tympanic membrane (TM) or eardrum were characterized at high strain rates after multiple exposures to blast waves. Human cadaveric temporal bones were subjected to blast waves at first, then TM strip specimens were prepared either along the radial or the circumferential direction. A highly sensitive miniature split Hopkinson tension bar was used for tensile experiments on the human eardrum strip specimens at high strain rates. The mechanical properties of the human TMs before and after exposure to blast waves were compared and discussed. The mechanical properties in the time-domain were subsequently converted to the corresponding properties in the frequency domain to investigate the effect of blast waves on the viscoelastic properties. The results indicate that the blast waves have different effects on the mechanical properties in the radial and circumferential directions. After exposure to the overpressure induced by the blast waves, the mechanical behavior in the radial direction in general becomes stiffened, while it is weakened in the circumferential direction. The results could be analyzed further in an ear simulation model to develop understanding of the effect of blast waves on hearing loss.

Keywords Human eardrum · Blast wave · Young's modulus · High strain rate · Split Hopkinson tension bar · Complex modulus · Frequency domain

Introduction

In the United States and the rest of the world, bombing attacks by terrorists or in battleground impose an increasing risk to personal injuries. A blast injury consists of four phases: primary, secondary, tertiary, and quaternary blast injuries [1, 2], and the greatest concern being the primary blast injuries. The eardrum or tympanic membrane (TM) rupture has been traditionally considered as a biomarker for blast injuries in ear and other organs. Blast induced hearing loss is categorized into TM perforation or rupture, cochlear hair cell damage, and rupture of round window [3]. The TM rupture results in acute hearing loss, tinnitus, pain, and dizziness. Although most injuries can be spontaneously healed through a period of time, permanent hearing loss often occurs [4]. When exposed to blast waves, there is a 16 % chance for a person to have TM perforation to induce damage in both ears. Hearing loss occurs commonly in the middle to high-frequency range [5] and there are more instances of hearing loss reported than vestibular or balance disorders. For curing, the most effective measure is to avoid exposure to other blast waves that might induce additional auditory injuries. However, in conflict zones, exposure to the multi-blast waves is often inevitable, especially for those far away from the blast sites, who are exposed to blast waves at magnitudes near or below a threshold pressure that can still develop hearing loss even if they do not show visible blast injury [6, 7].

The eardrum or tympanic membrane separates the middle ear from the outer ear, receives the sound waves collected by the outer ear, and transmits them to the middle ear. The TM plays an important role in coupling sound pressure wave in the ear canal with ossicular vibration in the middle ear. The damage in the TM caused by various diseases, pathological conditions, and blast wave, can

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contribute to different levels of conductive hearing loss [8–13].

The eardrum is a multi-layer membrane including the epidermal, collagen fibrous and mucosal layers. The collagen fibers provide primarily the mechanical stiffness of the TM. It consists of a matrix of ground substance embedding approximately 22 μm thick of collagen fiber layer aligned primarily along the radial direction emanating from the umbo, and approximately 15 μm thick collagen fiber layer along the circumferential direction [14]. A major part of TM is the pars tensa, which is within tympanic annulus ring located at the boundary; the malleus manubrium bone is attached in the central portion at the medial side. The small dimensions of the TM (about 70 μm thick and 9 mm in diameter) make it difficult to measure the mechanical properties. Numerous investigations of the mechanical behavior of human TMs have been performed at low strain rates or low frequencies [15–20]. The Young's modulus of a human TM strip specimen was reported as 10–20 MPa. Some of these property values are often used as input to model sound transmission and hearing sensitivity in middle ear [21, 22]. Accurate measurements of TM dynamic properties will help to understand the effects of structural changes of the TM, such as trauma by blast wave and infection, on the sound transmission and conductive hearing loss through modeling [23, 24].

The eardrum is subjected to loading in the frequency domain. The Young's modulus of the TM at high frequency was reported as 40 MPa in the circumferential direction at a frequency of 890 Hz [25]. Since the TM performs its function in the frequency domain, its mechanical properties must be characterized within the auditory frequency range, or high strain rates, for use to model the acoustic wave transmission in human ear. It is well known that for most biological tissues, the mechanical properties are not sensitive to strain rate under relatively low strain rate range [26]. However, their mechanical properties can change rapidly at high strain rate as tissues are relatively soft materials in which high strain rate behavior corresponds to their behavior towards glassy state. Recently, the Young's modulus of human TMs has been measured at high strain rates, corresponding approximately to the behavior in the higher frequency regime using a split Hopkinson tension bar (SHTB) [27, 28]. The results show a strong rate-dependent behavior for TM. In the study of traumatic blast injuries, the ear is one of the most vulnerable organs affected by the blast wave. Recently, the effects of acute and repeated exposure to blast overpressure in rodents were evaluated in order to help better understand the potential ramifications for injury in humans exposed to blast [29]. A blast chamber was set up to produce blast waves with profiles similar to that induced by explosives, in order to develop a reproducible

mouse model to study blast-induced hearing loss [30]. A bench model consisting of a simplified ear canal, eardrum, and middle ear cavity was tested in a blast chamber for high intensity sound transmission, and the experimental data were compared with the simulation results from a finite element model within the CFX/ANSYS environment [31].

In this paper, we use a highly sensitive miniature SHTB to measure the mechanical properties of human eardrum after exposure to blast waves at high strain rates, corresponding approximately to the behavior at high frequencies, and compare the properties with the corresponding results from the control TMs which are not subjected to blast waves. The control and blast-exposed human TM specimens were prepared in the radial and circumferential directions, and tested on the SHTB to determine the Young's modulus at high strain rates. The results are converted to the complex modulus in the frequency domain. The viscoelastic properties of TMs after exposure to blast waves are compared and discussed with the control (normal) TMs.

Experiments

Exposure of Human TMs to Blast Waves

Fresh human cadaveric temporal bones, including the complete normal organ of the ear, were obtained from Life Legacy Foundation, a certified human tissue supply source for military research. The study protocol was approved by the US Army Medical Research and Materiel Command (USAMRMC) Office of Research Protections (ORP). All experiments on human temporal bones were performed in the Biomedical Engineering Lab at the University of Oklahoma. A temporal bone containing an intact TM and ossicular chain with the pinna attached was mounted to a specifically designed “head block” inside the test chamber (Fig. 1a, b). A compressed air (nitrogen)-driven blast apparatus located inside the chamber was used to mimic blast exposure in this study. A polycarbonate film (McMaster-Carr, Atlanta, GA) of either 130 or 260 μm thick was used as a diaphragm, the rupture of which under compressed air generated blast overpressure of at least 207 kPa (30 psi, corresponding to 200 dB sound pressure level). The overpressure level applied on a TM was controlled by varying the distance from the blast reference plane.

A pressure sensor (Model 102B16, PCB Piezotronics, Depew, NY) was placed at the entrance of the ear canal (approximately 1 cm off the center of the ear canal opening) to monitor the blast pressure as shown in Fig. 1b. The pressure signal at P_0 was acquired by the cDAQ 7194 and

Fig. 1 The setup for the blast chamber that was used to induce blast waves to apply on a human TM bulla. **a** An overview of the blast chamber; **b** A zoomed-in view of human temporal bone bulla embedded inside a dummy head

A/D converter 9215 (National Instruments Inc., Austin, TX) with a sampling rate of 100 ks/s (10 μ s interval). The LabVIEW software package (NI Inc.) was used for data acquisition and analysis. Before blast test, two control TMs were harvested, the information of which is shown in Table 1. The remaining temporal bones were divided into two groups. One group was exposed to blast waves for four times with an average peak pressure of 33 kPa (4.8 psi, as measured at P_0) without inducing TM rupture. This group of TM information is shown in Table 2. Another group was subjected to three to four times of blast exposure as the peak pressure increases with the number of exposures until

reaching a peak value of approximately 66.5 kPa (9.5 psi) to induce rupture in the TM. The information for this group of TMs is shown in Table 3. After exposures to blast waves, the TM was harvested from the temporal bone for preparation of strip specimens for dynamic tensile experiments on the miniature SHTB.

Preparation of Human TM Strip Specimens

The control TMs with the tympanic annulus and malleus attached (Fig. 2), were harvested from two TM bullas. After the TM bullas were exposed to multiple blast waves,

Table 1 Control TM sample information and SHTB results

TM sample	Information	Location	Strain rate (s^{-1})	Modulus E (MPa)	Maximum stress reached σ_m (MPa)	Maximum strain reached ε_m (%)
TB 15-16R	64, F, R	1T	596	25.6	3.9	25
		2T	744	28.2	1.6	24
		3T	368	32.8	6.0	15
		4T	562	27.3	4.1	21
		5T	1365	51.8	19.1	50
		6T*	334	24.3	1.8	14
TB15-17L	79, M, L	1R	1280	39.4	6.2	24
		2R	518	37.7	4.8	22
		3R	885	34.4	2.5	34
		4R	1590	39.0	9.8	22
		5R1*	154	31.6	2.2	7.0
		5R2*	392	55.2	11.5	16
		6R*	171	3.21	1.9	8.0

M male; *F* female; *R* right ear; *L* left ear. Location 1T, 1R, etc. are labeled in Fig. 4. *T* transverse direction, *R* radial direction

* At a lower strain rate, the TM did not rupture and a second SHTB impact experiment was conducted. TB15-xx is the sample code for TM; the number in the information column is the age

Table 2 Blast-exposed (non-ruptured) TM information and SHTB results

TM sample	Information	Location	Strain rate (s ⁻¹)	Modulus E (MPa)	Maximum stress reached σ_m (MPa)	Maximum strain reached ε_m (%)
TB 15-7L	79, M, L (non-ruptured)	2R	841	55.1	4.4	11
		3R	558	53.2	15.1	20.8
		5R	946	90.2	10.0	9.2
		6T	1168	78.3	6.6	6.6
TB15-8R	58, M, R (non-ruptured)	2R	848	50.5	4.70	20.3
		3R*	359	48.9	7.40	16.2
		4T	913	21.4	8.10	38.3
		5T*	422	26.2	5.80	18.4
TB15-18R	79, M, R (non-ruptured)	1T	1550	24.3	6.50	45
		2T*	312	22.4	3.80	14
		3T	746	39.3	3.50	16
		4T	603	34.8	9.30	18
		5T	544	29.1	6.70	19
		6T*	306	50.9	8.50	14
		7T1*	385	11.7	2.00	16
		7T2*	358	12.6	2.60	15
TB15-19L	75, M, L (non-ruptured)	1T*	305	42.4	6.10	12
		2T	706	18.6	3.20	15
		4T	762	17.6	2.30	34
TB15-20R	75, M, R (non-ruptured)	1T	1578	19.0	3.20	30
		2T	944	29.1	4.90	22
		3R*	246	32.9	3.30	11
		4R*	148	24.3	1.10	6.5
		6R*	212	36.2	8.00	34

The group marked with “non-ruptured” indicates that after 4 times of exposure to the same level of blast waves, the TMs did not rupture
M male; *F* female; *R* right ear; *L* left ear

* At a lower strain rate, the TM did not break and a second SHTB tensile experiment was conducted. TB15-xx is the sample code for TM; the number in the information column is the age

the same procedure was used to harvest the blast-exposed TMs. The harvested TMs were immediately immersed in 0.9 % saline solution. A surgical knife was used to cut the pars tensa of the TM into strip specimens. Each TM strip specimen had dimensions of 1–1.5 mm wide and 4–5 mm long. The axial (length) direction of each strip specimen is along approximately either the radial or circumferential direction. In the case where a TM ruptured, the length direction of a TM specimen was mainly along the crack edge of the ruptured TM, in order to prepare as many strip specimens as possible. The specimens for measurement of Young’s modulus in the radial direction were cut along the radial fibers emanating from the umbo to annulus, and the specimens for measurement of the circumferential direction were cut nearly along the local circumferential fiber direction. After cutting, each strip specimen was placed back immediately into the saline solution again, and was used in dynamic tension experiment within 30 min. Unlike the control TMs in which TM

strip specimens were cut only for one orientation from one TM, for blast-exposed TMs, TM strip specimens with different orientations were cut from each TM, in order to prepare as many strip specimens as possible. TM strip-specimen orientations for ruptured TMs are shown in Fig. 3, and for un-ruptured TMs the specimen orientations are shown in Fig. 4. In this investigation, two control (healthy, without subjecting to blast exposure) TMs were used in order to compare results. In our previous work, we have conducted experiments on control TMs [27, 28], they were prepared from 11 normal TMs. In this investigation, 9 TMs were subjected to blast waves, they were then used for dynamic tension on SHTB at high strain rates. A list of control TM specimens with the age and side information is given in Table 1. Table 2 includes information for the five non-ruptured TMs after 4 times of exposure to blast waves with consistent pressures, and Table 3 contains information for the four ruptured TMs after 3–4 times of exposure to blast waves with increasing pressures.

Table 3 Blast-exposed (ruptured) TM information and SHTB results

TM sample	Information	Pressure at rupture (kPa)	Location	Strain rate (s^{-1})	Modulus E (MPa)	Tensile strength σ_m (MPa)	Failure strain ϵ_m (%)
TB 15-4R	64, M, R (ruptured)	84.1	1R	846	48.6	7.1	32.5
TB15-5L	73, M, L (ruptured)	77.6	2R	2756	54.3	17.6	41.2
			3R	935	83.7	26.6	20.5
			4R	1110	76.5	12.5	19.4
			5T	404	66.8	4.0	5.2
TB15-6R	73, M, R (ruptured)	118.6	1T	1405	77.2	30.4	36.2
			2T	1013	20.1	17.0	21.5
			3T	1637	50.9	12.4	19.4
			4T	868	77.2	21.2	20.9
			5T	1226	23.2	3.60	19.2
			6T	931	33.0	12.4	40.6
TB15-15L	64, F, L (ruptured)	108.9	1R	1580	96.0	5.80	6.2
			2R	635	83.0	3.40	5.0
			3R	1410	37.1	7.60	20
			4T	965	37.3	10.8	22
			5R	512	34.5	2.70	8.0

The TMs listed in this table were exposed to increasing levels of blast pressure for 3–5 times until rupture. TB15-xx is the sample code for a TM; the number in the information column is the age

M male, *F* female, *R* right ear, *L* left ear

Fig. 2 Control TMs that would be cut into strip specimens as marked. **a** TB15-16R (control, i.e., healthy undamaged TM not exposed to blast waves); **b** TB 15-17L (control). Note, some TMs were damaged during the harvesting procedures, rather than due to exposure to the blast waves

SHTB Experiments

A highly sensitive miniature SHTB was used for tensile tests of TM strip specimen at high strain rates. A schematic diagram for the SHTB setup is shown in Fig. 5. The incident bar was a 3.66 m long aluminum 7075-T6 bar with 6.4 mm diameter. The transmission bar was a 2.74 m long

hollow 6061-T6 bar with 5 mm inner diameter and 6.4 mm outer diameter. A pair of clamp fixtures made by 7075-T6 aluminum was used to grip a TM strip specimen. An aluminum tube striker bar was launched to make impact with a flange which was threaded to the incident bar end to load the specimen. Two semiconductor strain gages with a gage factor of 176 were attached on the opposite surfaces of the

Fig. 3 Blast-exposed TMs (ruptured) that would be cut into strip specimens as marked. **a** TB15-4R; **b** TB 15-5L; **c** TB15-6R; **d** TB 15-15L. Note, the TMs ruptured due to exposure to the blast waves

Fig. 4 Blast-exposed (non-ruptured) TMs which would be cut into strip specimens as marked. **a** TB15-7L; **b** TB 15-8R; **c** TB15-18R; **d** TB 15-19L; **e** TB15-20R. Note, the TMs were damaged during the harvesting procedures, rather than due to the blast waves

hollow transmission bar, at a distance of 17.8 cm from the clamping fixture, to measure the transmitted strain signal. A HBM Genesis 5i digital oscilloscope (25 Ms/s, 15-bit resolution, 1 MHz frequency bandwidth) was used to acquire all strain signals on bars through a Wheatstone bridge and Vishay 2310B signal-conditioning amplifier (up to magnification of 11,000, 180 kHz response frequency).

A plastic collar was used as a pulse shaper to provide assistance to generate dynamic stress equilibrium on the TM strip specimen and to reach a constant strain rate condition. The miniature SHTB was used to test both control and blast-exposed human TM specimens under high strain rates. Additional details on the SHTB are documented elsewhere [27, 28].

Fig. 5 Schematic diagram of a highly sensitive miniature split Hopkinson tension bar setup

With the use of a clamping fixture between the TM strip specimen and a bar end, in a valid SHTB experiment, the formulas for the stress and strain rate in a specimen are given as [32, 33]

$$\sigma_s(t) = \frac{A_t}{A_s} E_t \varepsilon_t(t) \quad (1)$$

$$\dot{\varepsilon}_s(t) = \frac{1}{L_s} [(c_i - c_t \beta) \varepsilon_i(t) - (c_i + c_t \beta) \varepsilon_r(t)] \quad (2)$$

where $\beta = E_i A_i / (E_t A_t)$; E , c , ε , σ , A and L are Young's modulus, bar wave speed, strain, stress, cross-sectional area, and length, respectively; the subscripts i , t , r represent the incident, transmitted, reflected signals, respectively. The subscript s indicates specimen. The strain history is obtained through the integration of strain rate with respect to time. Note that, for the soft TM tissue with Young's modulus in the neighborhood of tens of MPa, the typical maximum strain in a TM specimen is relatively high, on the order of 10–30 %, and therefore the compliance of the metal clamp fixtures is negligible. On the clamping fixtures mounted on two bar ends, two mini-aluminum bolts were used to tighten aluminum end plates to grip a TM strip specimen. During the gripping of a specimen, a small droplet of saline was added to the TM specimen surface to ensure that it was saturated with saline at all the time. The tensile tests were conducted at 23 ± 2 °C under relative humidity 40 ± 5 %. In this work, in order to apply preconditioning, we slightly stretched the TM strips to flat form for several times by wood sticks with round edge. Then a TM specimen was clamped for tensile test at high strain rates. Tensile tests for the control and the blast-exposed TM strip specimens were conducted within three ranges of strain rates, namely, 100–500, 500–1000 and 1000–2500 s^{-1} .

Experimental Results

TMs After Exposure to Blast Wave

In the blast experiments, the pressure in the compressed air cylinder for the shock tube was set to 2.0 MPa. The intensity of blast wave decreases with the increase of the distance from the blast nozzle. For the group one TMs (Table 2), each TM was subjected to 4 times of consistent pressure profile as shown in Fig. 6 and did not break. For the group two TMs (Table 3), each TM was subjected to increasing pressure with an increment of approximately 15 kPa in peak pressure between neighboring exposures until reaching 66.5 kPa to induce rupture of the TM. As shown in Fig. 6 during the blast duration of 0.7 ms, the

four waves were very similar to each other, indicating a good repeatability of the blast chamber. After 1.0 ms, there were fluctuations in pressure waves, and those waves were slightly different, but their magnitudes were much smaller than earlier waves, they are not anticipated to affect results in this study.

It is noted that in Figs. 2, 4, the damages in the TMs were induced during harvesting of the TM, rather than due to the blast waves. In Fig. 3a–d, the damages (cracks) in the 4 blast-exposed TMs were the results of the exposure to the multi-blast waves. In Fig. 3, crack locations are spread out; they are not concentrated at a particular quadrant of the TM. The cracks are in general along the radial direction, indicating that the circumferential fibers fractured.

SHTB Results

The input and output signals from incident bar, transmission bar, and X-cut signals are shown in Fig. 7a. They are similar to the data obtained in our previous work on control TMs [27, 28]. The force at the end of the strip specimen in contact with the incident bar, labeled as “front force”, was measured by the X-cut quartz. The data in Fig. 7a is analyzed to evaluate the dynamic stress equilibrium and strain rate history on a TM specimen; these results are shown in Fig. 7b. Both conditions are satisfied, indicating a valid experiment at a high strain rate. The data is processed further to determine the stress–strain relationships. Typical stress–strain curves are plotted in Fig. 8, they are mostly linear until fracture, very similar to our previously reported results. Figure 8 shows typical stress–strain curves of TM strip specimens in the radial and circumferential directions at high strain rates. Note that TM specimens did not necessarily break at these strain rates. The maximum strain experienced in each experiment was limited by the loading duration time of the miniature SHTB. Since this study

Fig. 6 The pressure histories for typical blast waves on TM measured by pressure sensor P_0

Fig. 7 Typical SHPB results. **a** Recorded signals from incident bar, transmission bar, and X-cut crystal. **b** Examination of dynamic stress equilibrium and constant strain rate history on a TM specimen

focused on the TM properties after exposure to blast wave, two control TMs as shown in Fig. 2a, b were used in SHTB test, to investigate if the TMs in this batch have similar properties as those from our previous batch. For control TM strip specimens in the radial and circumferential directions, the Young's modulus values are summarized in Table 1. The SHTB results include strain rate, maximum stress and strain achieved by the SHTB setup.

In order to compare the experimental data at different strain rates, the Young's modulus values are averaged within one of the three strain rate ranges, 100–500, 500–1000 and 1000–2500 s^{-1} , respectively. The average Young's modulus values of blast-exposed TMs within different strain rate ranges in this work are given in Table 2 for non-ruptured TMs, and Table 3 for ruptured TMs,

Fig. 8 Typical stress–strain curves of blast-exposed TM strip specimens in the radial and circumferential directions at high strain rates. Note that the TM specimens did not break at strain rates less than 500 s^{-1} . The strain rates of 246, 841, 1580, 312, 746 and 1226 s^{-1} were used for testing TM specimens TB15-20R-3R, TB15-7L-2R, TB15-15L-1R, TB15-18R-2T, TB15-18R-3T, and TB15-6R-5T, respectively

respectively. Within each range of strain rate, the Young's modulus is rather scattered. There is no clear trend to indicate a difference in results from the ruptured or non-ruptured TMs after exposure to blast waves. Since the number of data points in each group is not big enough, we therefore collect all data in both groups and analyze all the data together. Figure 9a, b show our previous results for the Young's modulus of normal TMs at different strain rates in the radial direction and the circumferential directions, respectively. The data shows about 20–30 % variation in Young's modulus obtained from different TM specimens [28]. The data was fitted into a model (in Discussion Section). In Fig. 9a, b, the error bar was plotted, representing 20 % deviation. A summary of the average data obtained in our previous work for control TMs [28] is given in Table 4. For control TMs, the Young's modulus as a function of strain rate is plotted in Fig. 9c, d in the radial and circumferential directions, respectively. The fitted curves in Fig. 9a, b with error bars are plotted to check if the data is in the 25 % deviation range. For two control TMs, one TM was used to cut strip specimens along the radial direction, and the other one was used to prepare strip specimens along approximately the circumferential direction. Each TM was cut into 6 or 7 pieces of strip specimens, and two or three TM specimens were tested under each of three strain rate ranges. The Young's modulus values of this batch of control TMs used in this work are similar to values obtained previously [27, 28], they are still within the range of the fitted curve of the control TMs in previous work [27, 28]. Results indicate that different batches of control human TMs give reasonably consistent results. This provides assurance to use our previous control TM results for comparison with results obtained from blast-exposed TMs, to investigate the effect of the blast wave on the TM mechanical properties.

The Young's modulus data for blast-exposed TMs under high strain rates are summarized in Table 5. Two typical

Fig. 9 Comparison of Young's modulus of TMs at different strain rates. **a** Control TMs in the radial direction [28]; **b** control TMs in the circumferential direction [28]; **c** control TMs in the radial direction; **d** control TMs in the circumferential direction; **e** blast-exposed TMs in the radial direction; **f** blast-exposed TMs in the circumferential direction

Table 4 Mechanical properties of healthy (control) human eardrum [28]

Eardrum	Number of TM specimens	Strain rate (s^{-1})	Young's modulus (MPa)	Maximum stress reached (MPa)	Maximum strain reached	Fiber direction
Healthy TM without subjecting to a blast wave	11	309 ± 77	45.2 ± 10.2	6.3 ± 3.4	11 ± 3	R
	15	714 ± 146	51.4 ± 16.6	10.4 ± 3.4	$20 \pm 7 \%$	R
	7	1654 ± 381	58.9 ± 18.5	15.9 ± 7.3	$41 \pm 10 \%$	R
	21	333 ± 68	34.1 ± 11.2	4.3 ± 1.8	$11 \pm 2 \%$	C
	6	772 ± 176	40.6 ± 7.6	7.7 ± 2.5	$14 \pm 8 \%$	C
	7	1353 ± 362	56.8 ± 15.7	13.7 ± 5.5	$37 \pm 10 \%$	C

R radial direction; C circumferential direction

blast-exposed TM strip specimens after tensile testing at strain rates higher than 500 s^{-1} are shown in Fig. 9. From these results, the Young's modulus as a function of strain rate is plotted in Fig. 9c, d for blast-exposed TMs in the radial and circumferential directions, respectively.

Figure 10 shows typical broken TM strip specimens after tensile experiments on SHTB. Figure 10a–d show failure patterns for control TMs in the circumferential direction, control TMs in the radial direction, blast-exposed TMs (TB15-15L-3R) in the radial direction, and blast-exposed TM (TB15-18R-7T) in the circumferential direction, respectively. The control TMs show ductile fracture pattern in both the radial and the circumferential directions (Fig. 10a, b). However, blast-exposed strip TM specimens with length in the radial direction still show ductile failure mode (Fig. 10c) with the fracture surface in a 45 degree inclined with respect to the loading direction, but the blast-exposed TM strip specimens with length along the circumferential direction show a brittle failure pattern (Fig. 10d), as indicated by the orientation of fracture surface which is perpendicular to the fiber direction.

Discussions

Viscoelastic Properties in the Time-Domain

The results obtained for blast-exposed TMs indicate that the Young's modulus values of these TMs depend on the strain rate within high strain rate range. Since data for the Young's modulus has been obtained within three ranges of high strain rates ($300\text{--}2000 \text{ s}^{-1}$), the mechanical behavior of the TM was described as a standard linear solid with three undetermined parameters. Figure 11 shows the standard linear model consisting of two springs, with spring constants E_∞ , E_1 , and a dashpot with viscosity η .

The relaxation time of the model is $\tau = \eta/E_1$. For a standard linear solid under the uniaxial tension, the Young's relaxation modulus $E(t)$ is given as

$$E(t) = E_\infty + E_1 e^{-\frac{t}{\tau}} \quad (3)$$

For a linear viscoelastic material loaded at a constant strain rate $\dot{\epsilon}_0$, the strain history is $\epsilon(t) = \dot{\epsilon}_0 t$.

An approach has been developed to convert the relaxation modulus to Young's modulus at different strain rates for eardrum [27, 28], foam [34] and resin [35]. For a linearly viscoelastic material under uniaxial stress state, the uniaxial stress $\sigma(t)$ is calculated from the applied strain history $\epsilon(t)$, using the Boltzmann superposition principle

$$\sigma(t) = \int_0^t E(t-\xi) \frac{d\epsilon(\xi)}{d\xi} d\xi \quad (4)$$

where $E(t)$ is relaxation modulus at time t . At a constant strain rate, $\epsilon(t) = \dot{\epsilon}_0 t$, where $\dot{\epsilon}_0$ is the constant strain rate, Eq. (4) becomes

$$\bar{E}(t) = \frac{\sigma(t)}{\epsilon(t)} = \frac{1}{t} \int_0^t E(\xi) d\xi \quad (5)$$

where $\bar{E}(t)$ is the average uniaxial relaxation modulus from time 0 to t . Eq. (5) indicates that the Young's relation modulus at a given strain rate is equal to the time-averaged relaxation modulus.

From an experimental stress–strain curve, the Young's modulus is determined within the limit of linearity, ϵ_e . The time t at the limit of linearity is determined by $t = \epsilon_e / \dot{\epsilon}_0$. Considering the standard linear solid model given in Eq. (3), the Young's modulus $\bar{E}(\dot{\epsilon})$ as a function of strain rate $\dot{\epsilon}_0$, which is also the average relaxation modulus $\bar{E}(t)$ up to time t (i.e., the elapsed time when strain reaches ϵ_e), is given as

$$\bar{E}(\dot{\epsilon}) = E_\infty + \frac{E_1(1 - e^{-\frac{\epsilon_e}{\tau}})}{\epsilon_e} \tau \dot{\epsilon} \quad \text{and} \quad (6)$$

$$\bar{E}(t) = E_\infty + \frac{E_1(1 - e^{-\frac{t}{\tau}})}{t}$$

Table 5 Mechanical properties of blast-exposed human eardrum

Eardrum	Samples	Strain rate (s^{-1})	Young's modulus (MPa)	Maximum stress reached (MPa)	Maximum strain reached %	Specimen orientation
Blast-exposed	4	241 ± 36	35.6 ± 10.2	5.0 ± 3.3	17 ± 12	R
	8	765 ± 171	62.4 ± 20.4	9.3 ± 8.1	15 ± 10	R
	4	1714 ± 721	66.0 ± 25.7	10.9 ± 5.3	21 ± 15	R
	7	356 ± 49	33.3 ± 20.7	4.7 ± 2.3	14 ± 4	C
	10	798 ± 149	33.7 ± 17.1	8.6 ± 5.5	25 ± 9	C
	7	1368 ± 237	41.9 ± 26.8	11.9 ± 9.3	28 ± 13	C

R radial direction; C circumferential direction

Fig. 10 Typical failed TM strip specimens after SHTB test. **a** A control TM in the circumferential direction; **b** a control TM in the radial direction; **c** TM (TB15-15L-3R) in the radial direction after blast wave; **d** TM (TB15-18R-7T) in the circumferential direction after blast wave

Fig. 11 A standard linear solid model

All the individual Young's modulus data (as shown in Tables 1, 2, 3) at the actual strain rates measured in SHTB tests are used as inputs to fit into Eq. (6), to search for the three best-fit parameters E_∞ , E_1 , and η . Table 6 summarizes the three best-fit parameters for both control and blast-exposed TMs in the radial and circumferential directions. Hence the best-fit Young's modulus is plotted in Fig. 12 as a function of strain rate (10^2 – $2 \times 10^4 \text{ s}^{-1}$) for TM in either the radial or the circumferential direction. Although the mechanical property data points are scattered within certain range, which is a common phenomenon for bio-tissues, the curves in general represent the trend reasonably well with the experimental data. With these curves, the Young's modulus can be determined at strain rates within 300 – 2000 s^{-1} . Figure 12 summarizes all fitting curves for comparison. The y-axis error bars show 20 % deviation, they are plotted to represent the data scattering.

Different phenomena could happen for TMs in the radial direction or in the circumferential direction after exposure to blast waves. At strain rates lower than 300 s^{-1} data for both control and blast-exposed TMs do not show much difference. When the strain rate is higher than 300 s^{-1} , up to 2500 s^{-1} , the Young's modulus becomes in general significantly higher than that of TMs without subjecting to

exposure to blast waves. However, for the TMs in the circumferential direction, the Young's modulus of blast-exposed TM decreased in tested strain rate range (300 – 2500 s^{-1}). As the strain rate becomes higher, the modulus becomes higher as well. These results indicate that the fibers in the radial direction of the TMs become stiffer, while the fibers in the circumferential direction become weaker after exposure to blast waves. This could be due to the fact that there are more collagen fibers along the radial direction ($\sim 22 \mu\text{m}$ thick layer) than in the circumferential direction ($\sim 15 \mu\text{m}$ thick layer) [14], and the blast waves generate a biaxial tensile stress state in a TM. Assuming each collagen fiber has about the same mechanical behavior, the difference in collagen fiber thickness in the radial and circumferential directions can give up to nearly 45 % of difference in mechanical properties (e.g., Young's modulus, tensile strength, etc.) in the two directions (radial vs. circumferential). Thus, under biaxial tension during blast pressure, the collagen fibers in the circumferential direction are expected to experience a higher stress (nearly 45 % higher) than the collagen fibers in the radial direction. When the blast pressure approaches the critical threshold value for rupture, it is easier for collagen fibers in the circumferential direction to rupture. On the other hand, the collagen fibers in the radial direction are expected to experience lower stress, thus will not experience rupture under a blast pressure that induces rupture in the collagen fibers in the circumferential direction. Therefore, the blast wave would cause some circumferential fibers to break, inducing cracks along primarily the radial direction. The radial fibers, however, are largely intact, they have gone through multi-blast waves, and tend to develop crystallization due to increased alignment of the collagen fibers, and as a result, they become stiffer.

Table 6 Best-fit parameters for Young's relaxation modulus

Eardrum	Modulus coefficient E_{∞} (MPa)	Modulus coefficient E_1 (MPa)	Relaxation time τ (10^{-5} s)	Specimen orientation
Control	41.5	25.4	5.07	R
Control	30.0	69.1	2.53	C
Blasted	30.1	52.6	10.3	R
Blasted	28.5	35.5	2.61	C

R radial direction; C circumferential direction

Fig. 12 Summary of fitted curves for the Young's modulus of control and blast-exposed TMs as a function of strain rate

With the parameters in Eq. (6) determined, the Young's relaxation modulus $E(t)$ can be determined. The Young's relaxation modulus was obtained for TM strip specimens in both the radial and the circumferential directions, as shown in Fig. 13. For the TMs in the radial direction, there is a crossing of the relaxation curves for control and blast-exposed TMs; there exists a critical time, $\sim 1.5 \times 10^{-4}$ s, below which the relaxation modulus of blast-exposed TMs is higher than that without blast; above that time, the relaxation modulus is lower. However, for the TMs in the circumferential direction, the relaxation modulus of blast-exposed TMs is lower than that without blast; the difference in the relaxation modulus beyond the critical time is smaller than that below the time.

Viscoelastic Properties in the Frequency Domain

The relaxation modulus in the time domain was converted to the complex modulus in the frequency domain. The complex modulus and the loss tangent are expressed as

$$\tilde{E}(\omega) = E'(\omega) + iE''(\omega), \text{ and } \tan\theta = \frac{E''}{E'} \quad (7)$$

where $E'(\omega)$ is the storage modulus and $E''(\omega)$ is the loss

Fig. 13 Comparison of Young's relaxation modulus between control and blast-exposed TMs in the time domain

modulus. For the standard linear solid in the frequency domain, the storage modulus $E'(\omega)$ and the loss modulus $E''(\omega)$ are calculated as [36–38]

$$E'(\omega) = E_{\infty} + \frac{E_1 \tau^2 \omega^2}{1 + \tau^2 \omega^2}, \text{ and } E''(\omega) = \frac{E_1 \tau \omega}{1 + \tau^2 \omega^2} \quad (8)$$

where ω is the angular frequency, $\omega = 2\pi f$, f is the frequency. The frequency f corresponds approximately to the strain rate [27, 28, 39] in the calculation of viscoelastic properties. The storage and loss moduli of TM are shown in Fig. 14a, b as determined using Eq. (8), respectively. The loss tangent values of TM in both the radial and circumferential directions are shown in Fig. 14c.

For TMs in the circumferential direction, the storage modulus, the loss modulus and the loss tangent curves have similar trends, as shown in Fig. 14a–c, respectively. The Young's modulus values of the TMs in the circumferential directions after exposure to blast waves are lower than those for control TMs. As the frequency becomes higher, the corresponding values of TM after blast decrease more rapidly than the control TMs, indicating that the blast waves have resulted in weakening of the circumferential collagen fibers. The blast-exposed TMs show less frequency-dependent viscoelastic effect than the control TMs

Fig. 14 Comparison of complex modulus between control and blast-exposed TMs in the frequency domain. **a** Storage modulus; **b** Loss modulus; **c** Loss tangent

in the circumferential direction, likely due to the significant damage developed in the collagen fibers in the circumferential direction. An eardrum is a multi-layer membrane including the epidermal, collagen fibrous and mucosal layers. The total thickness of a human eardrum is approximately 70 μm , among which, the collagen fibrous layer is approximately 37 μm (including 22 μm thick of

collagen fibers along the radial direction, and 15 μm thick of collagen fibers along the circumferential direction). The thickness of 70 microns was used to calculate the modulus data. Since the combined thickness of the collagen fibers in the radial direction is approximately 7 μm thicker than the combined thickness of collagen fibers in the circumferential direction, the mechanical behavior in the radial direction emanating from the umbo can be different from the corresponding behavior in the circumferential direction. Although the non-raptured TMs did not exhibit visible cracks, damage likely occurred in the collagen fibers along the circumferential directions, especially after exposure to repeated blast waves, leading to deterioration in mechanical properties. In the radial direction, however, due to the existence of thicker collagen fibers along this direction, the collagen fibers along the radial direction experienced stress levels less than a threshold value to induce permanent damage. Under exposure to repeated blast waves, the TM likely exhibits Mullin's effect, associated likely with the stress-induced crystallization or crosslinking in the collagen fibers. Additional investigation is needed to elucidate the mechanism behind the stiffening phenomenon in the radial direction in the future.

For TMs in the radial direction, the storage modulus, the loss modulus and the loss tangent show significantly different trends than those in the circumferential direction. There exists a critical frequency, ~ 900 Hz as shown in Fig. 14a, ~ 1500 Hz in Fig. 14b, and ~ 900 Hz in Fig. 14c, respectively. In Fig. 14a, below 900 Hz, the storage modulus of TM after exposure to blast waves is lower than that of the control TMs; after that, it becomes higher. It indicates that the blast waves induced higher frequency-dependent viscoelastic effect on TMs in the radial direction. In Fig. 14b, a peak value appears at ~ 1500 Hz for the loss modulus. The peak frequency decreases as compared to that of the control TM (not shown in Fig. 14b, the peak frequency is higher than 2500 Hz). The loss modulus of TM after exposure to blast waves is twice as high as that of the control TM. The loss tangent of TM after exposure to blast waves shows a much larger change, about three times as high as that of the control TM. This indicates that the blast wave causes very significant frequency-dependent behavior of TMs for TMs in the radial direction.

Conclusion

A blast chamber was used to induce blast wave to rupture TM under 35 kPa wave pressure for four times until the TM in the threshold or ruptures. A highly sensitive miniature SHTB was used to measure Young's modulus of both control TMs and blast-exposed TMs under high strain

rate 300–2000 s⁻¹. In the radial direction, the blast-exposed TMs has Young's modulus of 24.3–96 MPa, higher than the values of 45.2–58.9 MPa of the control TMs. In the circumferential direction, the blast-exposed TMs have Young's modulus of 11.7–78.3 MPa, less than the values of 34.1–56.8 MPa of the control TMs. A standard linear solid viscoelastic model was used to convert Young's modulus in the time domain into the complex modulus in the frequency domain. Blast waves cause significant changes on the mechanical properties of TM mainly due to the damage induced in the circumferential fibers and the stiffening in the radial fibers. From the viscoelastic property changes in the frequency domain, the blast-exposed TM show less viscoelastic effect in the circumferential direction, stronger viscoelastic effect in the radial direction.

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References

- Nakagawa A, Manley GT, Gean AD, Ohtani K, Armonda R, Tsukamoto A, Yamamoto H, Takayama K, Tominaga T (2011) Mechanisms of primary blast-induced traumatic brain injury: insights from shock-wave research. *J Neurotrauma* 28(6):1101–1119
- Mathews ZR, Koefman A (2015) Blast injuries. *J Emerg Med* 49(4):573–587
- Choi CH (2012) Mechanisms and treatment of blast induced hearing loss. *Korean J Audiol* 16:103–107
- Ritenour AE, Baskin TW (2008) Primary blast injury: update on diagnosis and treatment. *Crit Care Med* 36(7):S311–S317
- Shah A, Ayala M, Capra G, Fox D, Hoffer M (2014) Otolgic assessment of blast and nonblast injury in returning middle east-deployed service members. *Laryngoscope* 124:272–277
- Yeh DD, Schecter WP (2012) Primary blast injuries—an updated concise review. *World J Surg* 36:966–972
- Radford P, Patel HDL, Hamilton N, Collins M, Dryden S (2011) Tympanic membrane rupture in the survivors of the July 7, 2005, London bombings. *Otolaryngol Head Neck Surg* 145(5):806–812
- Hunter LL, Margolis RH (1997) Effects of tympanic membrane abnormalities on auditory function. *J Am Acad Audiol* 8:431–446
- da Costa SS, Paparella MM, Schachern PA, Yoon TH, Kimberley BP (1992) Temporal bone histopathology in chronically infected ears with intact and perforated tympanic membranes. *Laryngoscope* 102:1229–1236
- Ruah C, Penha R, Schachern P, Paparella M (1995) Tympanic membrane and otitis media. *Acta Oto-rhino-laryngologica Belg* 49:173–180
- Voss SE, Rosowski JJ, Merchant SN, Peake WT (2001) Middle-ear function with tympanic-membrane perforations. I. Measurements and mechanisms. *J Acoust Soc Am* 110:1432–1444
- Oktay MF, Cureoglu S, Schachern PA, Paparella MM, Kariya S, Fukushima H (2005) Tympanic membrane changes in central tympanic membrane perforations. *Am J Otolaryngol* 26:393–397
- Rosowski JJ, Nakajima HH, Cheng JT (2014) Current topics in the study of sound conduction to the inner ear, Chapter 26 in *Perspectives on Auditory Research*. In: Popper AN, Fay RR (eds) *Handbook of Auditory Research*, vol 50. Springer, Berlin, pp 493–511
- Lim DJ (1995) Structure and function of tympanic membrane: a review. *Acta Oto-rhino-laryngologica Belg* 49:101–115
- von Békésy G (1960) *Experiments in Hearing*. McGraw Hill, New York
- Dirckx JJ, Decraemer WF (2001) Effect of middle ear components on eardrum quasi-static deformation. *Hear Res* 157:124–137
- Fay J, Puria S, Decraemer WF, Steele C (2005) Three approaches for estimating the elastic modulus of the tympanic membrane. *J Biomech* 38:1807–1815
- Cheng T, Dai C, Gan RZ (2007) Viscoelastic properties of human tympanic membrane. *Ann Biomed Eng* 35:305–314
- Huang G, Daphalapurkar NP, Gan RZ, Lu H (2007) A method for measuring linearly viscoelastic properties of human tympanic membrane using nanoindentation. *J Biomech Eng-Trans ASME* 130:014501
- Daphalapurkara NP, Dai C, Gan RZ, Lu H (2009) Characterization of the linearly viscoelastic behavior of human tympanic membrane by nanoindentation. *J Mech Behav Biomed Mater* 2(1):82–92
- Gan RZ, Sun Q, Feng B, Wood MW (2006) Acoustic-structural coupled finite element analysis for sound transmission in human ear-pressure distributions. *Med Eng Phys* 28:395–404
- Wang X, Cheng T, Gan RZ (2007) Finite-element analysis of middle-ear pressure effects on static and dynamic behavior of human ear. *J Acoust Soc Am* 122:906–917
- Puria S (2003) Measurements of human middle ear forward and reverse acoustics: Implications for otoacoustic emissions. *J Acoust Soc Am* 113:3464–3481
- Ferris P, Prendergast PJ (2000) Middle-ear dynamics before and after ossicular replacement. *J Biomech* 33:581–590
- Kirikaie I (1960) *The Structure and function of the middle ear*. University of Tokyo Press, Tokyo
- Fung YC (1993) *Biomechanics: mechanical properties of living tissues*, vol 2. Springer, New York
- Luo H, Dai C, Gan R, Lu H (2009) Measurement of Young's modulus of human tympanic membrane at high strain rates. *J Biomech Eng-Trans ASME* 131(6):064501
- Luo H, Lu H, Dai C, Gan R (2009) A comparison of Young's modulus for normal and diseased human eardrums at high strain rates. *Int J Exp Comput Biomech* 1(1):1–22
- Ahlers ST, Vasserman-Stokes E, Shaughnessy MC, Hall AA, Shear DA, Chavko M, McCarron RM, Stone JR (2012) Assessment of the effects of acute and repeated exposure to blast overpressure in rodents: toward a greater understanding of blast and the potential ramifications for injury in humans exposed to blast. *Front Neurol* 3:32
- Cho SI, Gao SS, Xia A, Wang R, Salles FT, Raphael PD, Abaya H, Wachtel J, Baek J, Jacobs D, Rasband MN, Oghalai JS (2013) Mechanisms of hearing loss after blast injury to the ear. *PLoS ONE* 8(7):e67618
- Hawa T, Gan RZ (2014) Pressure distribution in a simplified human ear model for high intensity sound transmission. *J Fluids Eng* 136(11):111108
- Gray GT (2000) Classic split Hopkinson pressure bar technique', mechanical testing and evaluation. *ASM* 8:462–476
- Luo H, Lu H, Leventis N (2006) The compressive behavior of isocyanate-crosslinked silica aerogel at high strain rates. *Mech Time-Depend Mater* 10:83–111
- Luo H, Zhang Y, Wang B, Lu H (2009) Characterization of the compressive behavior of glass fiber reinforced polyurethane foam at different strain rates. *J Offshore Mech Arct Eng-Trans ASME* 132(2):021301

35. Luo H, Lu G, Roy S, Lu H (2013) Characterization of the viscoelastic behavior of bismaleimide resin before and after exposure to high temperatures. *Mech Time-Depend Mater* 17(3):369–399
36. Knauss WG, Emri I, Lu H (2008) Mechanics of polymers: viscoelasticity. In: Sharpe Jr, William N (eds) *Handbook of experimental solid mechanics*. Springer, USA, pp 49–96
37. Aerts JRM, Dirckx JJJ (2010) Nonlinearity in eardrum vibration as a function of frequency and sound pressure. *Hear Res* 263:26–32
38. Zhang X, Gan R (2013) Dynamic properties of human tympanic membrane based on frequency-temperature superposition. *Ann Biomed Eng* 41:205–214
39. Emri I, von Bernstorff BS, Cvelbar R, Nikonov A (2005) Re-examination of the approximate methods for interconversion between frequency- and time-dependent material functions. *J Non-Newtonian Fluid Mech* 129:75–84