Development of serial bio-shock tubes and their application

Wang Zhengguo 王正国, Sun Liying 孙立英, Yang Zhihuan 杨志焕, Leng Huaguang 冷华光
Jiang Jianxin 蒋建新, Yu Hongru 俞鸿儒, Gu Jiahua 谷家华 and Li Zhongfa 李仲发

Objective To design and produce serial shock tubes and further examine their application to experimental studies on blast injury.

Methods Bio-medical engineering technique was used for the design and development of the serial shock tubes. One thousand four hundred and fifty nine animals (757 rats, 105 guinea pigs, 335 rabbits, 240 dogs and 22 sheep) were then used to test the wounding effects of the shock tubes.

Results Three types of bio-shock tubes, that is, large-, medium- and small-scale shock tubes were made in our laboratory. The large-scale shock tube is 39 meters long; the inner diameter of the test section is 1 meter; and the maximum overpressure in the driving section is 10.3 MPa. A negative pressure could be formed by means of the reflected rarefactive wave produced by the end plate. The medium-scale shock tube is 34.5 meters long; the maximum overpressure in the driving section is 22 MPa; the test section is designed to be a knockdown, showing 5 basic types with inner diameter of 77 to 600 millimeters, which could be used for researches on overpressure, explosive decompression, underwater explosion, and so on. The small-scale shock tube is 0.5 meter long with the maximum endured overpressure of 68.6 MPa. Results from animal experiments showed that this set of shock tubes could induce various degrees of systemic or local blast injury in large or small animals.

Conclusions This set of bio-shock tubes can approximately simulate typical explosive wave produced by nuclear or charge explosion, and inflict various degrees of blast injury characterized by stability and reproducibility. Therefore, they can meet the needs of blast research on large and small animals.

Chin Med J 1998; 111(2): 109-113

Bio-shock tubes are the ones specially or mainly used for bio-studies. The shock wave induced by the bio-shock tubes is similar to the explosive wave produced by nuclear or charge explosion. Animals can be subjected to various degrees of blast injury when they are put in or at the open of the tubes. Therefore, the tubes can be used to reproduce ideal animal models for studies on pathogenesis of blast injury and its prevention and treatment.[1-6]

Several years ago, we successively developed a set of bio-shock tubes (large-, medium- and small-scale tubes), which is unique in our country, for blast injury research. Results from massive animal experiments indicated that this set of tubes could inflict various degrees (from mild to dead at the spot) of injuries on sheep, dogs, rabbits, guinea pigs, rats, etc.. They could also induce local injury of the eyeball, etc. at experimental requirement. Therefore, it could be concluded that this set of bio-shock tubes is an ideal experimental equipment and can meet the needs of blast injury research. The development of this set of shock tubes and their applications are summarized as follows.

DEVELOPMENT OF THE SERIAL BIO-SHOCK TUBES AND THEIR DESIGN PRINCIPLES

Large-scale bio-shock tube

The large-scale bio-shock tube (BST-Ⅰ, Fig. 1) is 39 meters long, consisting of driving, conical, transitional, test and wave-elimination sections, and auxiliary equipment such as air compressor, high-pressure air tank, etc.. A double-clamping-diaphragm structure is used. The driving section is 1.59 meters long, clamping diaphragm section 1.41 meters long. Their inner diameter is 0.348 meter. The conical section is 1 meter long with inner diameter of 0.348 to 1 meter, and wave-elimination section 11 meters long. The transitional and test sections are 24 meters long. The inner diameters of the latter three sections are 1 meter. The maximum overpressure in the driving section can reach 10.3 kPa

Research Institute of Surgery, The Third Military Medical University, Chongqing 400042, China (Wang ZG, Sun LY, Yang ZH, Leng HG and Jiang JX)

Institute of Mechanics, The Academy of Sciences of China, Beijing 100080, China (Yu HR, Gu JH and Li ZF)

This study has won the First Prize of National Sci-Tech Progress in 1992.

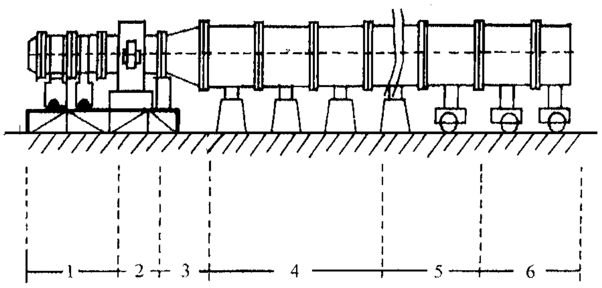

Fig. 1. A schematic drawing of BST-Ⅰ model. (1) Driving section; (2) Section for clamping diaphragm; (3) Conical section; (4) Transition section; (5) Test section; (6) Wave-elimination section.

(1 kPa = 7.5 mmHg). Our test results showed that in the open condition of the test section, its maximum overpressure was 0.219 MPa with a duration of 32.7 milliseconds, and negative pressure 0.09 MPa; while in its closed condition, its maximum overpressure might go up to 0.63 MPa with a duration of 24.5 milliseconds, suggesting that this large-scale shock tube could simulate the explosive wave produced by air explosion of tens to 6000 kg of TNT.

Design principles

Firstly, the reflected rarefactive wave produced by the cover of the driving section is kept moving in the same direction as shock wave in the tube. When the rarefactive wave catches up with the shock wave, the pressure of shock wave is then decreased rapidly. A negative pressure then occurs when the pressure value behind rarefactive wave is less than atmospheric pressure. Therefore, the tube could simulate an explosive wave characterized with both positive and negative pressures. Secondly, by means of a movable diaphragm, the length or intra-pressure of the driving section can be well regulated, which then changes the peak over- and under-pressure values and their duration in the test section, making the experimental parameters controllable. Thirdly, the utility of compressed air, rather than explosive air, as the driving force can prevent burns and intoxication apnea. Fourthly, the use of the diaphragms made of pure aluminum and bi-membrane gradient pressurization can accurately regulate the pressure value required to rupture the diaphragm and also prevent animals from fragment wound in the rupture of the diaphragm. Furthermore, a movable plate is installed at the end of the test section, which could mimic the explosion wounding conditions in open air or in the limited space.

Medium-scale bio-shock tube

The medium-scale bio-shock tube (BST-Ⅱ, Fig. 2) is 34.5 meters long. The length of the driving section is adjustable (from 0.5 to 0.8 meter long) with the maximum overpressure of 22 MPa and the inner diameter of 77 millimeters. The test section is designed to have 5 types of basic assemblies, of which the inner diameters are 77, 100, 200, 350 and 600 millimeters separately. Therefore, the tube can be used to simulate the explosive wave produced at the plateau, under water, explosive decompression, impact effects of high-velocity airflow, etc.. The overpressure values and durations are 2.52-650 kPa and 0.2-2000 millimeters, respectively, which could be changed by ±1 decibel (dB) and ±1 millimeters as a step to regulate the wounding conditions.

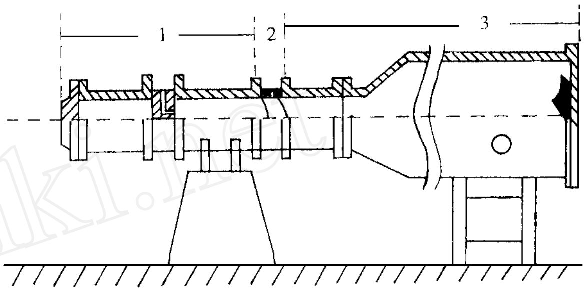

Fig. 2A. A schematic drawing of BST-Ⅱ model. (1) Driving section; (2) Clamping diaphragm; (3) Test section.

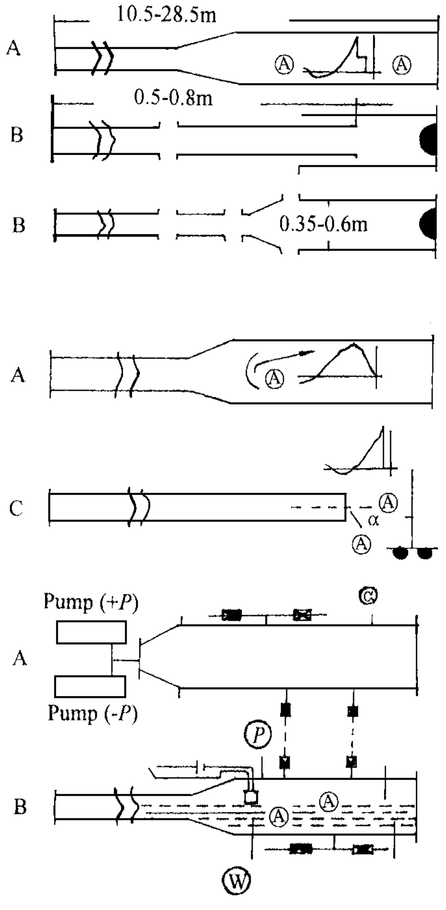

Fig. 2B. Test sections with different combination of the BST-Ⅱ model.

Design principles

The rarefactive wave in the driving section can catch up with shock wave, which is prerequisite to simulate the duration of overpressure of explosive wave induced by ten thousand-ton yield nuclear explosion. The length of the driving section can be changed by means of series connection, forming 12 types in length, which enhances the capacity and range of the tube to simulate explosive wave. In addition, the distance between the conical section and the end plate can make time difference between incident and reflected waves, which is necessary to simulate the wounding condition of two explosive waves when a person is at different distances to a reflected wall. The tube is designed to be airproof. Chambers A and B are equipped with under- and overpressure regulators, and water/gas supply system, which can keep intra-chamber atmospheric pressure at a low level before the rupture of diaphragm, thus simulating the explosive condition at the plateau or altitude flight. If the chambers are kept at high pressure or charged with water, it could simulate the underwater explosive condition which the drivers might encounter. Furthermore, the animal chamber can be rapidly recovered to the pre-injury condition through A or B chamber after wounding, which can improve the simulation authenticity. The end of the driving section is a hemisphere-shape blindness, which makes the rarefactive wave have asynchrony reflection, leading to obtain explosive wave with its duration of as much as 100 millimeters on the short equipment. Furthermore, the effects of focused shock wave could be studied, and the wounding intensity could be increased when experimental animals are put at the end of the test section.

Small-scale shock tube

The small-scale shock tube (BST-Ⅲ, Fig. 3) is 0.5 meter long with a maximum endured overpressure of 68.6 MPa. The test section has 9 types with inner diameter of 2 to 10 millimeters. The overpressure peak values and durations are 26.8—477 kPa and 0.062—16.8 millimeters, respectively. The tube is used to produce punctuate explosive wave, and allows exposure to explosive wave at a fixed distance, region and direction.

Design principles

This type of shock tube produces explosive wave by means of rapid rarefaction of shock wave in the air soon after it is transmitted out of the nozzle of the tube. The volume or pressure in the driving section can be regulated by steel fillers, thus enhancing the capability of the tube to produce different intensities of explosive wave. Through regulation of the distance from the nozzle of the tube to experimental animal, the intensity of explosive wave acted on the animal can be changed. Furthermore, through the nozzle of the guard shield on the tube, local blast injury research can be performed in fixed region or area. Moving the universal-tube support equipped on the shock tube is easy to change the direction of shock wave. In addition, transducers of pressure,

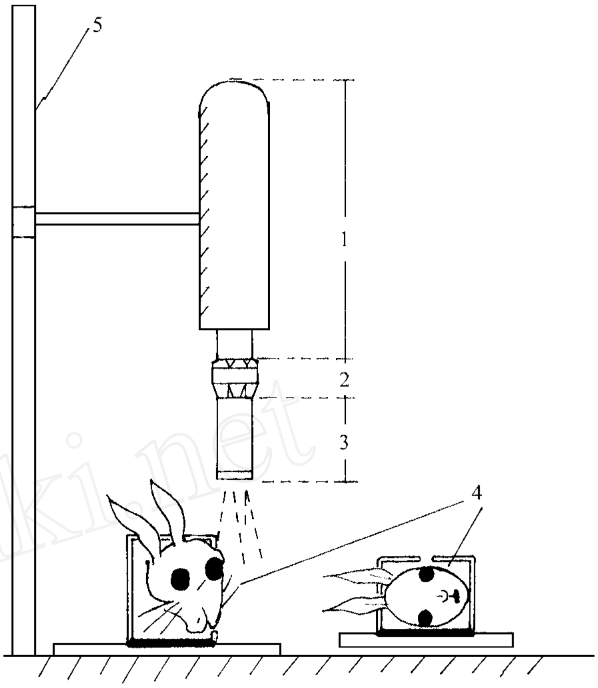

Fig. 3. Universal-tube support. (1) Driving section; (2) Clamping diaphragm; (3) Test section; (4) Tested rabbit; (5) Universal-tube support.

acceleration, displacement, etc. are permitted to be used in this tube to record the dynamic response induced immediately after explosive wave affecting organism.

BIO-EXPERIMENTS

Since the establishment of the bio-shock tubes, one thousand four hundred and fifty nine animals, including 757 rats, 105 guinea pigs, 335 rabbits, 240 dogs and 22 sheep, have been successively used to perform blast injury research, systemically or locally (such as on the eyes, ears, head, chest and abdomen), indicating this set of shock tubes could inflict various degrees of blast injury from mild injury of the acoustic organs to immediate death. Experiments on overpressure injury can be done when the plate is closed, while experiments on overpressure and dynamic-pressure combined injury can be done when the plate is open. Some of the experimental data are reported as follows.

Large-scale shock tube

Fifty two adult mongrel dogs, weighing 12.3 ±1.8 kg, were used. The blast injury was induced by BST-Ⅰ. The test parameters and occurrence of organ damage are shown in Tables 1 and 2. Seven out of 52 animals were dead within 5 minutes post injury, with 4 dying of severe pulmonary hemorrhage and edema, 2 of internal hemorrhage induced by hepatic and splenic rupture, and 1 of coronary arterial air embolus.

Table 1. Relationship between blast overpressure value and the severity of injury *

Groups	Peak values (kPa)	No. of animals	Occurrence of injury (No.)			
			Mild	Medium	Severe	Extremely severe
Close	200.2 - 245.4	14	10	3	1	
	298.0 - 322.2	10	4	6		
	361.2 - 418.2	13		4	6	3
	388.4 - 399.3	6				6
	620.3	1				1
Open	141.6 - 156.2	2	2			
	170.9 - 214.3	4		3	1	
	190.4 - 239.2	2			1	1

* The severity of blast injury is classified by our own established standards.

Medium-scale shock tube

Fifty rabbits were randomly divided into 5 groups (n = 10 for each group). The chest of animals in groups 1 and 3 was surrounded with a stripe, which could limit the expansion of the chest induced by blast wave, thus alleviating pulmonary injury. The animals in groups 2 and 4 were unprotective, and those in the group 5 were normal control. The results indicated that the hemorrhage area on the lungs was much less in groups 1 and 3 than in groups 2 and 4 ($P < 0.05$, Table 3).

Small-scale (micro-) shock tube

Studies of eye blast injury

Sixty rabbits were put separately 4 and 2 centimeters distant from the open of the tube. The eyes of the rabbits were in frontal or lateral exposure to shock wave. The peak values of the overpressure from which the experimental animals suffered were 477.2 ±42.4 kPa and 236.7 ±42 kPa, durations 8.2 ±0.3 milliseconds and 0.062 ±0.023 milliseconds. After wounding, myosis and increased tension of the eyeball occurred, accounting for 97.5 % and 80 % on the side of injured eye, and 22.5 % and 35 % on the side of normal eye, respectively. There were significant differences between the two eyes ($P < 0.05$). Pathological examination showed that the cornea, crystal, retina and uvea were subjected to damage in the injured eye. In the severe cases, break of the eyeball, severance of optical nerve occurred and even the eyeball was shocked out of the orbit. It was noticeable that the injury to the crystal and retina might occur while there was no obvious alterations in the cornea and anterior chamber in the injured eye.

Table 2. The occurrence frequency of injury in various organs

Groups	No. of animals	No. of the injured animals							
		Acoustic organ	Lung	Heart	Bladder	Intestine	Liver	Spleen	Stomach
Close	44	44	44	24	24	13	6	5	7
Open	8	8	8	7	5	3	4	4	1
Total	52	52	52	31	29	16	10	9	8
%		100	100	67	56	29	19	17	15

Table 3. Protective effect of chest stripe on pulmonary hemorrhage in rabbits *

Groups	n	BW (kg)	PHA (mm^2 / 100g BW)	L/B index	L/W index	Lethality (n)
1	10	2.2 ±0.3	16 ±15	0.652 ±0.190	0.810 ±0.002	0
2	10	2.2 ±0.4	101 ±71	0.544 ±0.102	0.767 ±0.005	0
3	10	2.5 ±0.6	19 ±18	0.588 ±0.297	0.824 ±0.003	0
4	10	2.2 ±0.2	107 ±70	0.509 ±0.107	0.791 ±0.004	2
5	10	2.5 ±0.2	0	0.512 ±0.022	0.633 ±0.009	0

BW: body weight; PHA: pulmonary hemorrhage area; L/B: lung/body; L/W: lung/water. * The peak values and durations of overpressure adopted in groups 1, 2 and groups 3, 4 were 262.5 ±11.4 kPa, 15.3 ±1.2 milliseconds and 296.2 ±3.2 kPa, 12.5 ±0.8 milliseconds, respectively.

Studies of thoraco-abdominal blast injury

Fifty rats, weighing 234 ±25 g, were evenly divided into 5 groups. Animals in groups 1 and 3 were subjected to chest injury, in groups 2 and 4 to abdominal injury, and in group 5 were control. The distance from the open of the tube to the animal was 15 millimeters in groups 1 and 2, and 135 millimeters in groups 3 and 4. The results indicated that when the chest was in exposure to shock wave, only chest injury (pulmonary hemorrhage) occurred without any damage to the abdominal organs, while the organs both in the chest and abdomen could be injured when the abdomen was in exposure to shock wave (Table 4), which might be related to sudden up-movement of the diaphragm when the abdomen was compressed.

DISCUSSION

The charge explosion was the main way to inflict injury in the previous studies of blast injury. Although this method is very similar to a real accident from an explosion, it is very difficult to get accurate experimental parameters and to perform early functional examination on animals on the spot. There are also some other problems, such as less stability and poorer reproducibility. However, the above shortcomings can be overcome by the use of shock tubes.

Some small-scale shock tubes used in laboratory were developed in 1950's in the United States and Sweden.[1-3] They were one to several meters long with an inner diameter of 0.1 meter. They consisted of the driving and test sec-tions, which were separated by a

Table 4. The occurrence of thoracic and abdominal organ injury in rats in local exposure to blast wave

Groups	Exposed region	Peak values (kPa)	Durations (ms)	PHA (mm^2 / 100 g BW)	L/B index	L/W index	GEH (mm^2)	HRR (%)	L_{30} (%)
1	Chest	231.9 ±24.2	38.6 ±10.4	483 ±47 *	0.98 ±0.14	0.720 ±0.065	0	0	100
2	Abdomen	224.6 ±28.5	35.4 ±6.8	114 ±42	0.81 ±0.12	0.861 ±0.042	18 ±11 *	100	100
3	Chest	173.7 ±27.4	43.0 ±8.7	29 ±8	1.24 ±0.07 #	0.902 ±0.085	0	0	0
4	Abdomen	186.3 ±44.1	49.8 ±12.7	12 ±7	0.71 ±0.11	0.981 ±0.055	2 ±3	0	0
5	Control	0	0	0	0.60 ±0.17	0.619 ±0.037	0	0	0

PHA: pulmonary hemorrhage area; L/B: lung/body; L/W: lung/water; GEH: gastroenteric hemorrhage; HRR: hepatic and renal rupture; L_{30}: lethality within 30 minutes after injury. * $P < 0.05$, compared with other groups; # $P < 0.05$, compared with group 4.

film in the middle of the tube. Studies, such as on the relationship between pressure values and lethality in mice, etc., have been performed using these tubes.

After 1960's, Richmond et al.[4-6] from the United States have successively developed 5 types of large- or medium-scale shock tubes, and systemically studied the wounding or lethal effects of blast wave on different animals under conditions of various peak values and durations. They further applied their results to human beings. In 1987, Jaffin et al[7] from the United States designed a micro-generator of shock wave. The volume of the driving section was 150 milliliters with maximum pressure of 10-25 MPa. One or several thick aluminum discs (0.36 mm) were used as diaphragm, which was ruptured by means of natural inflation. A small animal experiment could be done using this equipment.

The set of shock tubes made in our lab has been improved on the basis of previous work done by other researchers, showing the following main characteristics: 1) Our lab has been simultaneously equipped with large-, medium- and small-scale shock tubes, basically achieving the aim of seriation; 2) BST-Ⅰ adopts a new working principle, that is, the reflected rarefactive wave produced by the cover of the driving section catches up with the shock wave after rupture of the diaphragm. When the pressure value behind the reflected rarefactive wave is lower than atmospheric pressure, an underpressure wave is then produced. Therefore, it can simulate typical explosive wave. However, the bio-shock tubes developed in foreign countries, in general, could not produce typical underpressure wave, their simulation capacity is then much poorer; 3) The pressure value can be better regulated by means of a bi-diaphragm structure; 4) BST-Ⅱ is a multi-functional shock tube, it can simulate the explosive wave at the plateau, under water, explosive decompression, impact effects of high-velocity airflow, etc.; 5) Due to their seriation, the set of tubes can be extensively used for blast injury reseach, inflicting not only systemic injury in large and small animals (such as sheep, dogs, rabbits, rats, etc.), but also local injury, overpressure injury, overpressure and dynamic pressure combined injury, mild injury and lethal injury.

Based on the above analysis, it could be concluded that this set of shock tubes developed by us is advanced, and can better meet the requirements for experimental research in the field of blast injury.

Acknowledgement: The authors wish to thank Drs. Li Xiaoyan, Tang Chengong, Ma Xiaohua, Yi Yuguo, Zhao Min, Zhang Junkui, et al for their partial participation in this work.

REFERENCES

1. Cassen B, Curtis L, Kistler K. Initial studies of the effect of laboratory-produced air blast on animals. J Aviat Med 1950; 21: 38.

2. Cassen B, Kalian P, Gass H. High speed photography of the motion of mice subjected to laboratory-produced air blast. J Aviat Med 1953; 23:104.

3. Celander H, Clemedson CJ. A study of the relationship between the duration of a shock wave and the severity of the blast injury produced by it. Acta Physiol Scand 1955; 33:14.

4. Richmond DR, Clare VR, Goldizen VC, et al. Biological effects of overpressure (Ⅱ): a shock tube utilized to produce sharp-rising overpressures of 400 milliseconds duration and its employment in biomedical experiments. Aerosp Med 1961; 32:997.

5. Richmond DR, Goldizen VC, Clare VR, et al. Biological response to overpressure (Ⅱ): mortality in small animals exposed in a shock tube to sharp-rising overpressures of 3 to 4 msec duration. Aerosp Med 1962; 33:1.

6. Richmond DR, Damon EG, Bowen IG, et al. Air blast studies with eight species of mammals: Defense Atomic Support Agency Report (DASA). 1966: 1854.

7. Jaffin JH, Mckinney L, Kinney RC, et al. A laboratory model for studying blast overpressure injury. J Trauma 1987; 27: 349.

(*Received May 24, 1997*)

本文编辑: 曹琳冰