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Healing Touch Shocking Waves!

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ABSTRACT

The convergence of the various scientific disciplines brings with them multifaceted benefits. Scope of extending it to a wide range of biological systems from the simplest prokaryotic microorganisms e.g. bacteria to complex mammalian and plant cells proves the importance of interdisciplinary research in the interest of the human mankind. One such example of an interdisciplinary research field is the use of shockwaves. They are accompanied with almost all the processes involving rapid energy transformations. The energy associated with such waves is harnessed and used for various applications across diverse disciplines including aerospace and aeronautical engineering, material science and biological and biomedical sciences. There has been enormous development in the field of shock wave biology. Researchers across the globe have studied various interactions and effects of shock waves on biological systems. Extracorporeal shock wave lithotripsy is the most successful application of shock waves till date. Biomedical applications developed by us include needle-less drug delivery, bacterial transformation using shock waves, microbial biofilm disruption, shock wave responsive drug release formulations and shockwave assisted wound healing. This article highlights the basics of shock wave physics, methods developed by us to generate them and their biomedical applications.

Introduction

Shock wave is a term commonly associated with aerospace engineering and astronautics. They are generated in nature whenever different elements in a fluid approach one another, with a relative velocity higher than that of sound in the given medium[1]. Shock waves when traversing through a medium, give rise to perturbations (fluctuations) in the thermodynamic properties of the medium such as pressure, density and temperature. The intensity of these waves determines the magnitude of these perturbations. If the disturbance is weak, the propagation occurs at a relatively lower speed. On the contrary, if the disturbance is strong, the local properties and the speed change at a high rate within a very short time. Shock waves are such waves, which induce abrupt changes in the material properties. Unlike shock waves, sound waves are weak perturbed waves which do not alter the properties of the traversing medium.

In nature, shock waves are one of the most efficient mechanisms of energy dissipation. Energy dissipation occurrences such as explosions, lightning, volcanic eruptions and earthquakes; produce shock waves[2]. Simulating these conditions are used to produce shock wave in laboratory. For example, a rapidly moving piston in a tube filled with gas can generate shock waves, since the energy is released in a very short time (a few μs). Apart from mechanical energy, chemical, electrical or nuclear energy dissipation in a limited space can also generate shock waves[3]. Apart from the classical applications of shock waves, they have also been exploited in various trans-disciplinary areas like materials engineering, civil engineering, chemical kinetics and biomedical engineering. This article highlights the biomedical applications using shock waves, their brief history and novel strategies developed by us at the Laboratory of Hypersonics and Shockwave Research at Indian Institute of Science, Bangalore.

Background to biomedical applications of shockwaves

During the last 30 years, biomedical applications of shock waves have developed enormously and have been established in medicine for safe and effective treatments for several diseases. Extracorporeal shock wave lithotripsy (ESWL or SWL), i.e., the non-invasive use of shock waves to break up concernments formed inside the body, revolutionized the treatment of urolithiasis in the early 1980s and motivated considerable research. SWL to treat stones in the gallbladder, the common bile duct, the pancreatic duct, and the salivary gland ducts followed. Since then, researchers and clinicians across the globe have developed many such applications based on the Dornier Lithotripsy Device. Following section enlists the basics of Dornier lithotripter based medical devices.

Conventional methods of Shockwave generation and lithotripsy

The known methods to generate micro shock waves are pulsed laser beam focusing[4], micro-explosives for underwater shock wave generation, electro-hydraulic underwater shock-wave generator, electromagnetic shock wave generator and piezo-ceramic shock wave generator[5]**.** This system is commonly used for extracorporeal shock wave lithotripsy (ESWL). Dornier lithotripter is commercially used for ESWL. It uses a self-focusing parabolic reflector is mounted with piezoelectric crystals. When subjected to high voltage, compressive wave fronts are produced due to the vibration of individual crystals. Shock wave is formed at the focal point of the reflector. This design mainly consists of a source of shockwaves and a reflector-based focusing system. This methodology employs high energy acoustic waves, which when focused at a site are capable to disintegrating renal calculi. Figure 1 (a) depicts a typical setup used for focusing shockwaves at a point. Point F1 is the source whereas point F2 is the target site. The patient is usually made to lie under-water for the treatment. Figure 1 (b) shows the pressure profile generated in such a system. It is worth noting that the peak pressures achieved in this setting are in the order of 25-30 MPa.

This translates to roughly 300 bar at the point of focus. Human body can sustain peak pressures of not more than 8 bar. Therefore, a slight change in the focal point can lead to extensive collateral damage. Therefore, the conventional lithotripters face this limitation of only being used for destructive purposes like disintegrating kidney and gall stones. Another drawback of these devices is that the impulse of the shockwave cannot be controlled on the time axis. This calls for a need to develop devices which have mechanisms to precisely control the peak pressures as well as the decay time of the shockwave. With this motivation we have developed biomedical applications which need relatively low pressures/shockwaves and require a longer decay time and employs alternate strategies to generate shockwaves.

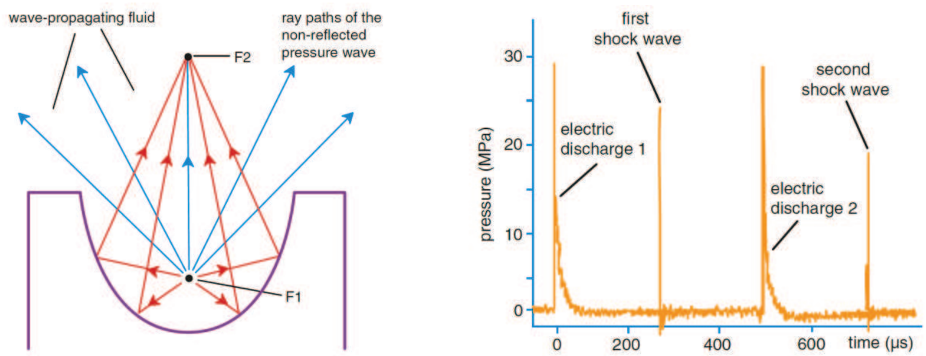


Figure 1: (a) A typical arrangement to focus shockwaves for lithotripsy. (b) A graph depicting the peak pressures generated during ESWL.

Novel Methods of Generating Shock waves developed at LHSR

Micro shock waves & their generation

There have been several attempts in the past to experimentally re-create a large-scale explosion in the laboratory using negligible amounts of primary explosives. Both silver azide and lead azide pellets have been successfully used in the past to generate micro-shock waves in the laboratory. Spherical shock waves can be generated in laboratory by focusing ND: Glass laser beam in air or water with radius of few mm. Since the energy used to generate the shock waves is ~1.38 J, it is called as micro shock waves. This energy is equivalent to 0.3 mg of conventional TNT explosives [5]. These shock waves can be generated by different methods in the laboratory. The generated micro shock waves can be used for different applications as well as to study the basic science associated with shock wave and material interactions. Following section describes the various methods to generate controlled shock waves and their applications.

Nonel Tube-based Shockwave Generator

The device called as the Nonel tube[6] employs a novel methodology to generate micro-shock waves in a repeatable and controlled manner, utilising small amounts of explosives. This simple prototype model efficiently transfers energy and shock waves to the sample. The device consists of an ignition system (Dyno nobel, Sweden), explosive-coated polymer tube (Dyno nobel, Sweden), metal foil, transformation chamber and cavity holder (Figure 3a). Once the polymer tube, ignited from one end rapid combustion of explosive material occurs causing shock waves to form. The metal foil prevents the combustion materials from polymer tube from entering the sample chamber (Figure 3c, d). The peak pressure achieved by the shock wave is around 60 bar with a steady time of 10 µs (Figure 3b)[7, 8]. This device has been successfully used to transform bacteria[9], deliver vaccine without needles[10], target bacterial biofilms[1] and to treat dental hypersensitivity[11].

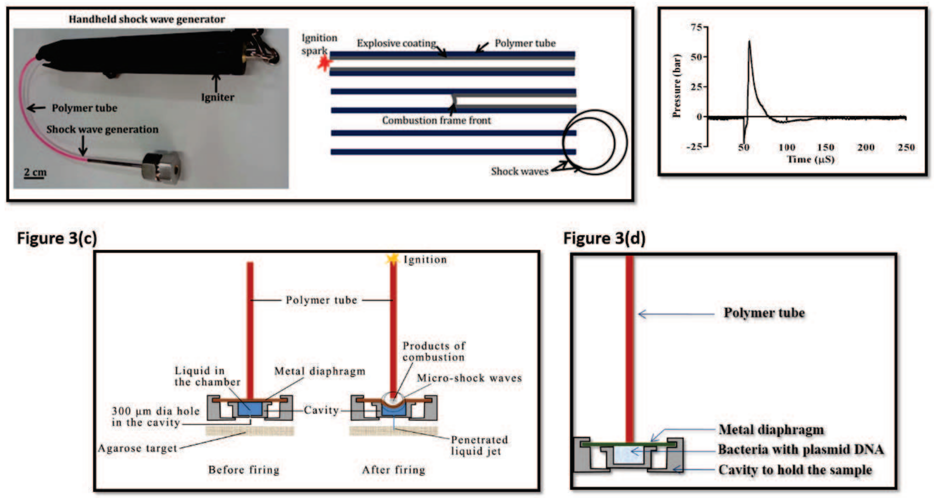
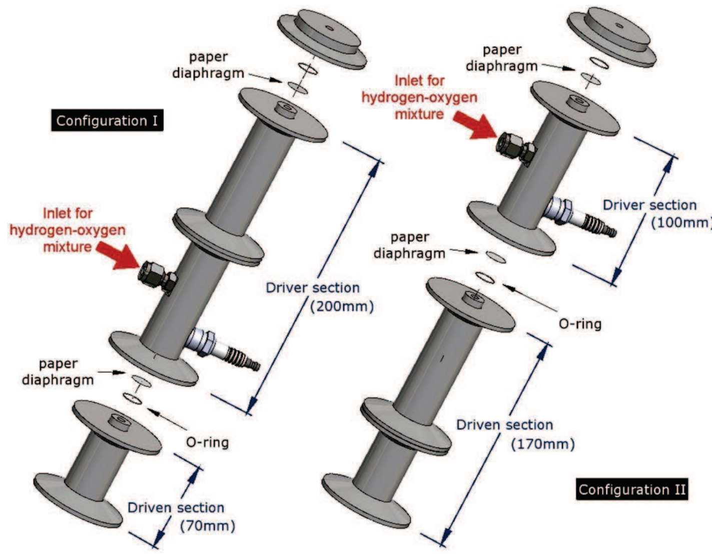
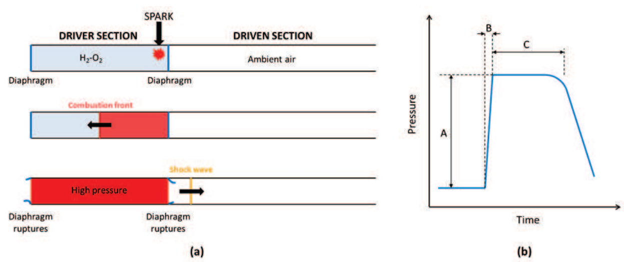


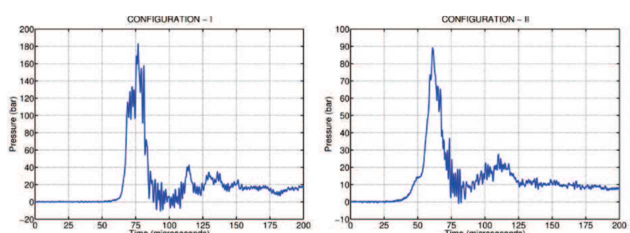
Figure 2: Micro-shockwave generator using explosives (Nonel Tube). (a) Handheld shockwave generator; schematic of shockwave generation after combustion of explosive material. (b) Typical shock profile obtained at the end of the polymer tube after combustion. (c) Schematic of arrangement of the Nonel tube for needle-less drug delivery and (d) for bacterial transformation.

Oxyhydrogen based Miniature Shock tube

Since the energy of the shock wave generated by Nonel tube was not tuneable, we developed the next generation shock tube which used combustion of insitu generated oxyhydrogen to generate shock waves. The device comprises of two main components - an oxyhydrogen generator and a miniature shock tube assembly. The oxyhydrogen generator produces the required amount of stoichiometric mixture of hydrogen and oxygen gases through alkaline electrolysis. A miniature shock tube assembly with an internal diameter of 6mm is used. The oxyhydrogen mixture is filled in the driver section of the shock tube (this is termed as initial fill pressure of oxyhydrogen henceforth) and a spark plug, placed close to the diaphragm station between the driver and the driven section, is used to ignite the mixture to produce a backward facing detonation front. The high pressure and temperature behind the detonation front causes the instantaneous rupture of the diaphragm between the driver and driven section and produces a strong shockwave in the driven section of the shock tube. Tracing paper (95 GSM) is used as diaphragm in the shock tube which can be replaced by a quick opening solenoid valve at a later stage. A tri-clover clamp is used between the different sections of the shock tube to facilitate quicker and easier changing of diaphragm after each experiment. The biological sample is accommodated in a stainless-steel sterile cavity of diameter 6mm and depth 5 mm. The optimization of the dimension of the cavity has already been reported. In a previous study, a brass foil was suggested as a viable option for energy transfer from the shock wave to the biological sample and to avoid contamination of the bacteria by the products of detonation. However, brass foil needs to be replacement after every experiment, and it absorbs most of the incident shockwave energy before transmitting it to the biological sample. Therefore, we have used a silicone rubber membrane to separate the cavity housing the biological sample from the shock tube. Silicone rubber is a biocompatible material which has a good tensile strength and is resistant to temperatures of up to 300 °C. These properties make it ideal for our application, as there is no need for frequent replacement and the energy transfer is much better as compared to using the brass foil. The impulse generated by this shock tube can be varied by varying the lengths of the driver and driven sections. Figure 3shows the impulse calculated for 2 different conditions. It can be observed that the tunability of this device makes it ideal for multiple biological applications as described in the later sections of this article.







Shock tube		Shockwave parameters		
Configuration	Fill pressure (bar)	Peak pressure (bar)	Pulse duration (μs)	Impulse (Pa.s)
I	3.0	183	31.9	214.6
II	3.0	89	48.6	122.1

Needle-less vaccine delivery

Bacterial transformation

Figure 3: Novel oxyhydrogen driven miniature shock tube for biomedical applications, it's working principle and impulse analyses.
(Datey et. al. Scientific Reports volume 7, Article number: 8645 (2017))

Piston Based Medical Device

An elastic wave may be generated in a liquid column by having a piston impacting the free surface of the liquid. This may also be the water hammer effect in Civil engineering literature. The amplitude of the pressure pulse, so generated, is proportional to the velocity of the piston, v_p. This gives rise to an elastic wave in the liquid medium that travels at the speed of sound in that medium.

$$p_0 = \rho a v_p$$

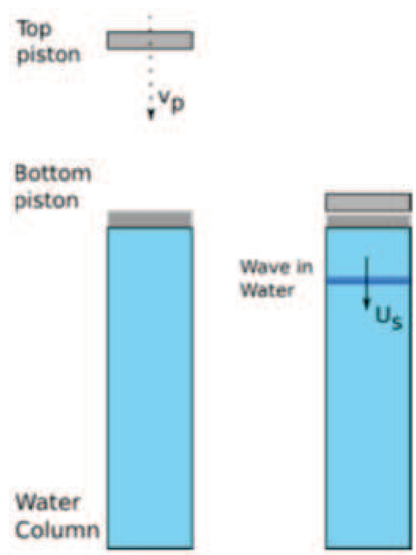


Figure 4: Design of the piston based medical device

By having a suitable membrane at the bottom of this column (typically water), we can have efficient transfer of the shock wave from this water column onto the other side of the membrane. The decay time (time constant, tau) of the wave depends on the mass of the piston and other physical and geometrical properties of the liquid medium.

$$\tau = \frac{m_p}{\rho a A}$$

Thus, by varying the piston velocity, and the piston mass, one can independently vary the pressure and the decay time of the pulse, thus achieving fine control over the shape of the pulse that may be produced using this device. By coupling this water column with a spring-based system to impart a modest velocity to a piston mass, one can have a handy system that can generate pressures up to 100 bar, with decay times of the range of 500 microsecs. This device is currently being developed as a point-of-care device exclusively for biomedical use.

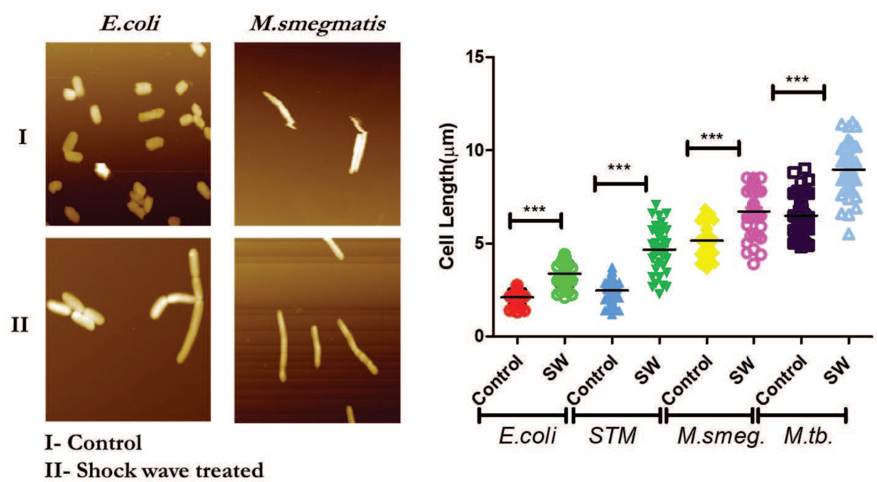
Biomedical applications of shock waves developed at the Laboratory of Hypersonics and Shockwave Research (LHSR), IISc.

Micro-shock wave assisted needle-less vaccine delivery

Needle injections are used popularly for vaccination and they are also the main source for HIV and other blood-borne viral infections. The available needle free injections have their own disadvantages. Nonel tube device generating micro-shock waves has been used for vaccination in an efficient, safer and cheaper way. Live attenuated typhoid vaccine (DV-STM-07) was administered to murine salmonellosis model. The efficiency of vaccination was found to be significantly high when compared to conventional routes of vaccine delivery. The device delivers vaccine in active epidermal layer of skin, where the most potent antigen presenting, Langerhans cells are present. The study highlights that only 10% of vaccination dose is required to elicit immune response as compared to other routes of vaccination[12, 13].

Bacterial Transformation using micro-shock waves

A tool for transferring DNA/RNA to the cells is an important requisite for basic as well as applied biotechnology and molecular biology studies. Liposome or polymeric based transfection agents, viral vectors and electroporation are the majorly used methods to transform living cells[14, 15]. Electroporation is a mechanical method where electrical discharge makes the cells permissive for the uptake of nucleic acids [16]. It was observed that when the cells were exposed to shock waves in the presence of nucleic acids, they could take up the DNA/RNA [17, 18]. Many dry particle delivery systems were developed using high pressure gases to accelerate particles for plant transformation. In 1987, Klein et al., and Sanford et al., first time demonstrated the plant transformation using a powder gun. DNA coated tungsten particles accelerated by the device were used to transform plant cells[19, 20].



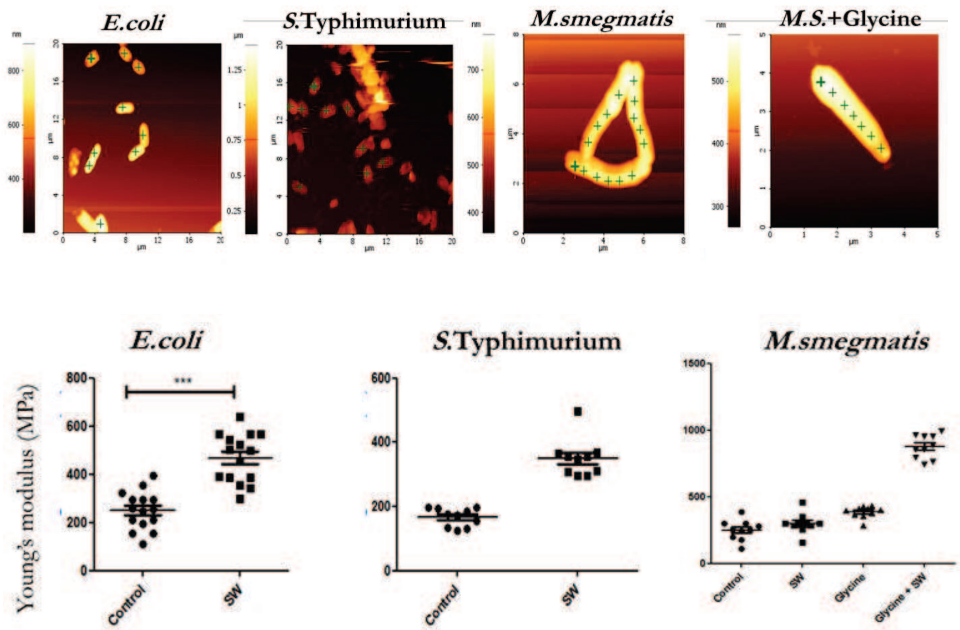


Figure 5: Biomechanical analyses of bacterial cells after shockwave exposure for transformation. Cell length and Young's Modulus measurements in bacteria.
(Datey et.al. *Scientific Reports* volume 7, Article number: 8645 (2017))

Shock waves are one of the most competent mechanisms of energy dissipation observed in nature. We have used the Nonel tube device as well thee oxyhydrogen driven shock tube to generate controlled micro-shock waves. The micro-shock waves have been used to transform various bacteria to achieve significantly higher transformation efficiency. The highest transformation efficiency achieved (1×10^{-5} transformants per cell) was at least 10 times greater than the previously reported ultrasound mediated transformation (1×10^{-6} transformants per cell). This method has also been successfully employed for the efficient and reproducible transformation of *Pseudomonas aeruginosa*, *Salmonella* Typhimurium and *Mycobacterium tuberculosis*. This novel method of transformation has been shown to be as efficient as electroporation with the added advantage of better recovery of cells, economical (40 times cheaper than commercial electroporator) and growth-phase independent transformation. Biomechanical analyses of the bacteria after shockwave exposure highlighted a transient increase in the cell length and Young's modulus. We hypothesize that this positive change in the Young's modulus causes a tremendous increase in the transformation efficiency (Figure 5)[21].

Shock wave responsive drug delivery system for therapeutic application

Different systems have been used for more efficient drug delivery as well as targeted delivery. Responsive drug delivery systems have also been developed where different stimuli (pH, temperature, ultrasound etc.) are used to trigger the drug release. In this study, we have developed a novel drug delivery system which responds to shock waves. Spermidine and DSS was used to develop the microcapsules using layer by layer method. Ciprofloxacin was loaded in the capsules and shock waves were used to release the drug. Only 10% of the drug was released in 24 h at pH 7.4, whereas 20% of the drug was released immediately after the particles were exposed to shock waves. Almost 90% of the drug release was observed when the particles were exposed to shock waves 5 times[22].

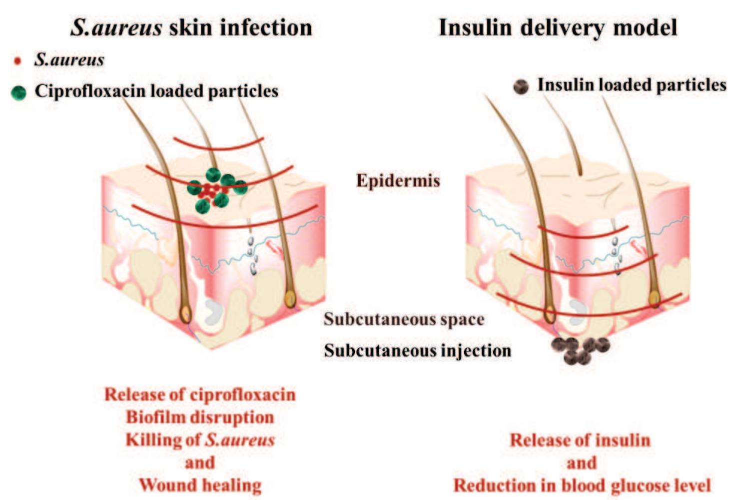


Figure 6: Schematic of Shockwave assisted targeted drug release for multiple applications
(Gnanadhas DP et.al. RSC Adv., 2015,5, 13234-13238)

Shock wave assisted bacterial biofilm disruption and clearance

The term "biofilm" was coined by Bill Costerton wherein microorganisms form micro colonies surrounded by copious amounts of exopolysaccharide with water filled channels in between which facilitates the influx of nutrients and efflux of waste products [9, 23]. Most of the microorganisms form micro-colonies and produce extracellular matrix to form biofilm which are not susceptible to antibiotics and other anti-microbial agents. This reduced susceptibility may be due to the presence of extracellular polymer matrix produced by the biofilm (intrinsic) or due to the transfer of extra chromosomal DNA from resistant organisms to susceptible organisms (acquired) [24]. Clinically these changes make the treatment for these biofilm infections very difficult.

Biofilm formation is commonly observed in medical devices and is difficult to get rid of. They can be formed in most of the medical devices including urinary catheters, central venous catheters, peritoneal dialysis catheters, intrauterine devices, endotracheal tubes, prosthetic joints, voice prosthesis, mechanical heart valves, pacemakers etc. [25]. *Escherichia coli*, *Pseudomonas aeruginosa, Streptococcus*, *Staphylococcus epidermidis* and *Staphylococcus aureus* are some of the major bacteria which form biofilms during the infectious stage. These pathogens come into contact with the surgical implants or catheters after the installation of implants and form biofilm [26]. Removal of the biofilm may require a 1000 times higher antibiotic dose to have the same therapeutic effect as in the case of s planktonic cells [27]. The removal of the implant is the only way to treat the biofilm infection in these cases [28]. Antibiotics and antimicrobial peptides coated implants have been developed to control the biofilm formation in these implants [26].

Apart from formation of biofilm in medical devices, many of the pathogenic bacteria are found to produce biofilm which cause inflammation and tissue damage [29, 30]. Upper respiratory tract which includes the nose, pharynx, larynx and sinuses is an ideal site for biofilm formation primarily due to its warm and moist nature making them prone to infections. Rhinosinusitis is the inflammation of the nasal passages and sinus cavities. Planktonic bacteria released from these biofilms can multiply and disperse in the host. This makes the scenario more complicated as these planktonic bacteria can infect other parts of the body and form biofilm. Though the planktonic bacteria are susceptible to antibiotics, the infection recurs until the biofilm communities are removed completely.

A few reports suggest that laser generated, and extracorporeal shock waves can cause damage to the biofilm[31, 32]. However, the effect of shock waves on biofilm has not been studied in detail. A method which uses micro-shock waves to disrupt *Salmonella*, *Pseudomonas* and *Staphylococcus* biofilms in catheters has been described. Exposure to shock waves physically disrupts the biofilm ultimately making it susceptible to antibiotics. Apart from shock wave mediated disruption of biofilm on medical devices, we also demonstrated that controlled shock waves can be used to efficiently treat *Pseudomonas* lung infection in mouse model and a polymicrobial biofilms can be treated from patient samples[1].

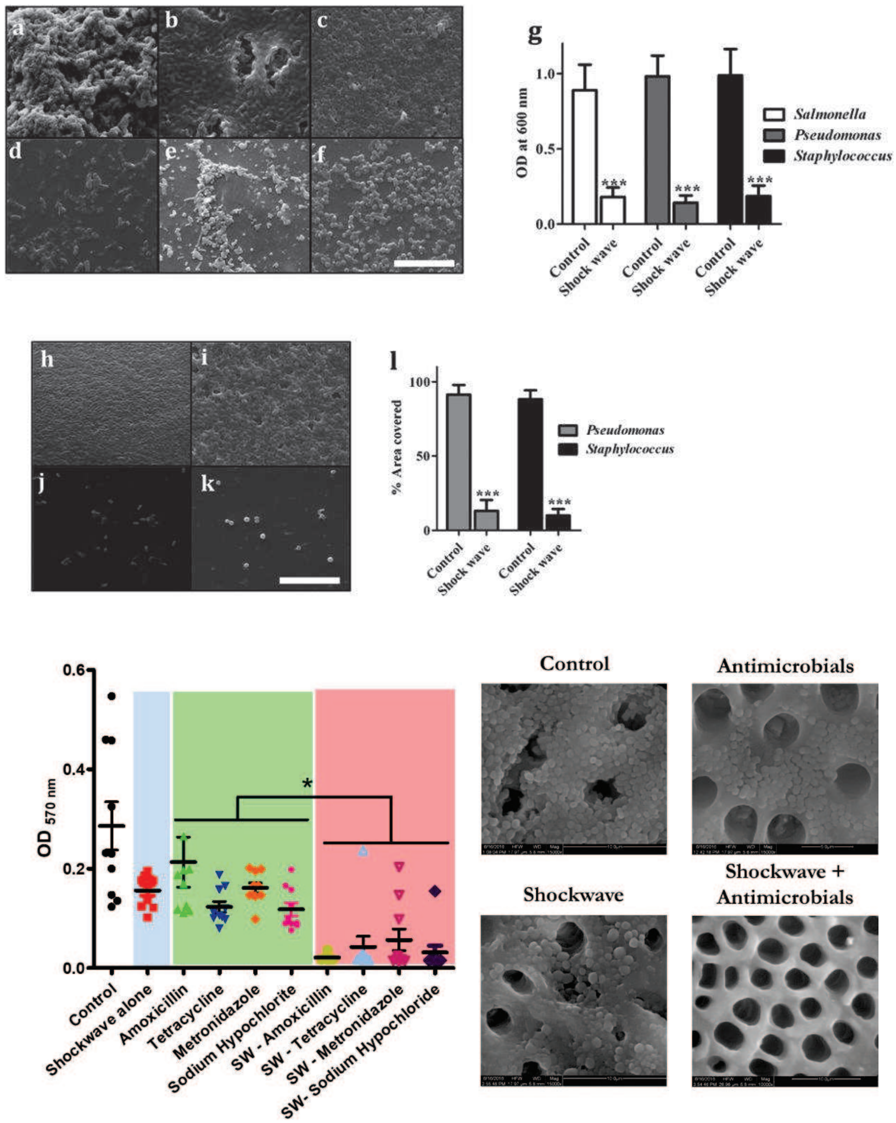


Figure 7: Shockwave based biofilm disruption in vitro and polymicrobial biofilm disruption using shockwaves and antimicrobials from periodontitis patient samples

Shock wave mediated treatment of dentinal hypersensitivity

Dentinal hypersensitivity is characterized by the presence of exposed dentinal tubules caused by abrasion and consumption of acidic foods and beverages[33]. The exposure of these tubules to certain stimuli which include hot, cold or sour items causes movement of the fluid in the dentinal tubules causing sharp pain[34]. This condition causes extreme discomfort. If left untreated, it leads to worsening of the condition. Dentists all over the globe prescribe toothpastes containing desensitizing agents like salts of calcium, potassium, strontium etc. These salts occlude the exposed dentinal tubules causing a temporary isolation of the tubules from the environmental stimuli[35]. The occlusion provides temporary relief to the patient but with the passage of time and regular brushing and the normal fluid flow in the oral cavity, the occluding material is washes away. In this study. The authors have demonstrated the successful use of micro-shock waves in combination with commercially available desensitizing toothpastes to treat dentine hypersensitivity in a significantly better way. These waves have been effective in enhancing the efficiency of tubule occlusion by desensitizing agents. The number of dentine tubules occluded by shock waves applied after the desensitizing agent was shown to be significantly higher than the occluded tubules after application of desensitizing agents alone. The plugs formed in the shock wave treated specimen were also shown to be resistant to acid and carbonated drink challenges. Thus, micro-shock waves can be used for effectively treating dentinal hypersensitivity along with available desensitizing agents[11].

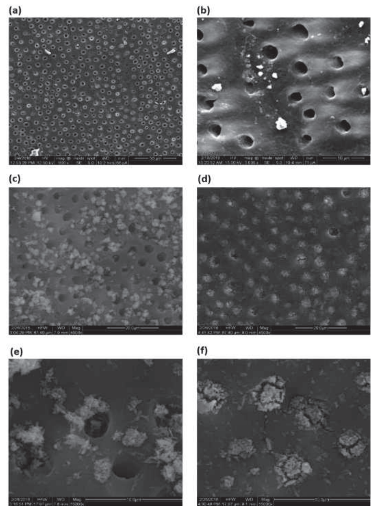


Figure 8. Cross sectional SEM micrographs of dentine surface morphology and occlusion (if any) by desensitizing agent present in the tooth paste of (a) Control group; (b) Shockwave (SW) alone group; (c) Desensitizing Agent (DS) alone group and (d) DS followed by SW application (e-f) DS and DSSW at 15000X magnification.

Non- invasive angiogenic therapy for chronic-wound healing

In recent times, low energy shock waves have been employed as a non-invasive angiogenic therapy [36] [37]. Shock waves (0.09 mJ/mm^2) applied to the ischemic region over a period of 4 weeks normalized myocardial function and blood flow. It was also found to increase capillary density and VEGF expression, thereby emphasizing its effectiveness in the treatment of ischemic heart disease [37]. Endothelial cells respond to mechanical stimuli such as stretch. This property can be exploited with caution to induce angiogenesis which will have immense potential to treat pathological conditions associated with insufficient angiogenesis. The primary aim of this study is to test if low-pressure shock waves can be used to induce angiogenesis. Using a simple diaphragm-based shock tube, we demonstrate that a single pulse of low pressure (0.4 bar) shock wave is enough to induce proliferation in bovine aortic endothelial cells and human pulmonary microvascular endothelial cells. We show that this is associated with enhanced Ca^{++} influx and phosphorylation of phosphatidylinositol-3-kinase (PI3K) which is normally observed when endothelial cells are exposed to stretch. We also demonstrate the pro-angiogenic effect of shock waves of single pulse (per dose) using murine back punch wound model. Shock wave treated mice showed enhanced wound-induced angiogenesis as reflected by increased vascular area and vessel length. They also showed accelerated wound closure compared to control mice. Overall, our study shows that just a single pulse/shot (per dose) of shock waves can be used to induce angiogenesis. Importantly, we demonstrate this effect using a pulse of low-pressure shock waves (0.4 bar, in vitro and 0.15 bar, in vivo)[38].

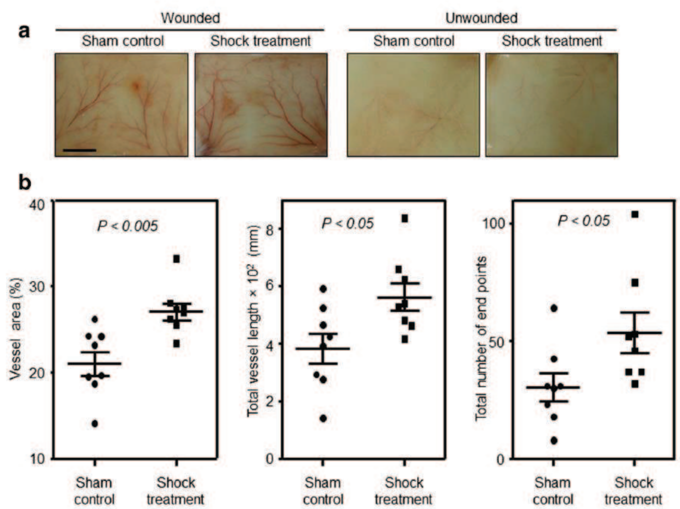


Figure 9: Effect of shockwaves on angiogenesis in vivo (Sundaram et.al. JMolMed, 2018)

Shock wave treatment for wound healing

Shock wave treated Wistar rats indicated a significant reduction in the wound size and topical pro-inflammatory reaction and an increase in the blood perfusion. Similarly, increase was also observed in VEGF, eNOS and PCNA expression [39]. Diabetic ulcer is a serious complication of diabetes which eventually leads to amputation due to frequent wounds. However, 20 weeks of ESWT was found to facilitate complete wound closure [40]. Shockwave therapy was found to be effective against full thickness open wound as it reduced both infiltrating neutrophils and macrophages. We also found that shockwave cause a suppression of proinflammatory cytokines, chemokines and matrix metalloproteinases produced by cells at the wound site.

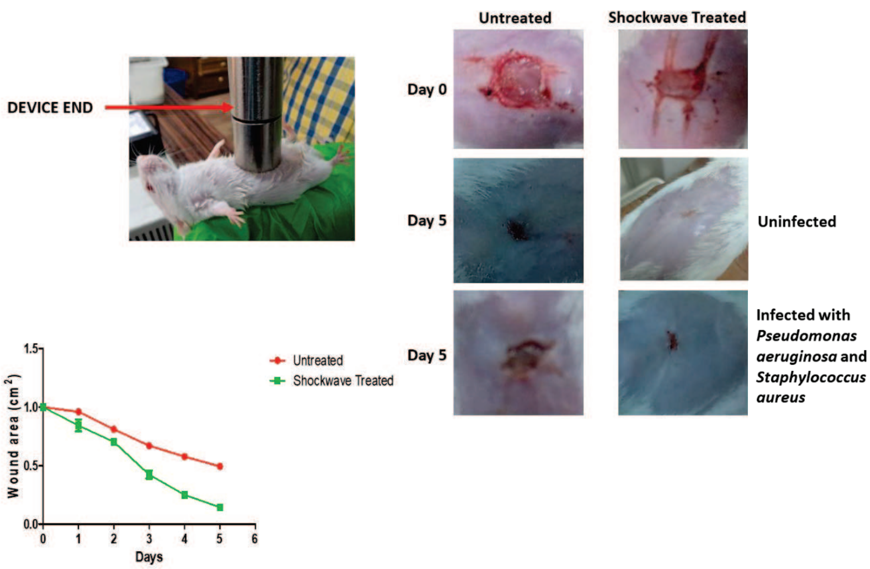


Figure 10: Shockwave based wound healing in diabetic mouse model

Shock wave therapy in reproductive system

Erectile dysfunction is a sexual condition where the individual is unable to develop or maintain an erection of the penis during intercourse. This condition is currently treated with intercavernosal injections of vasodilating agents and oral phosphodiesterase type 5 inhibitors, though it is not able to modify the pathophysiology. Shock wave is found to be a better modality of treatment as it is able to induce neovascularization which leads to increased cavernosal arterial blood flow, one of the underlying causes of ED [41]. There are several studies analyzing the effect of ESWT in male and female reproductive systems [42-45]. We have also developed a protocol to treat ED using low intensity shockwaves. The preliminary data suggests that low intensity shockwaves can alleviate the condition of ED in more than 75% of the subjects.

A novel conical shock-tube for simulating conditions for trauma-induced blast wave injury

Shock tubes generally produce blast waves having a longer decay time and they also have a huge amount of gas that continues to exit the shock tube for quite some time after the shock has passed the specimen. Needham et al. [46] in his recent work has suggested the use of the appropriately scaled dosage of impulse for a given animal size and the elimination of the gas jet from the exit of the shock tube. Needham et al. [46] provide guidelines, from the perspective of a fluid dynamicist, on what one needs to be careful about while carrying out blast injury studies on animals. They bring out the role of blockage, especially in experimenting with living beings, where the chances of accumulating damage over wrong loading can lead to inaccurate conclusions. While a shock tube with a conical attachment at the end does better in this regard, they suggest that the fluctuations in the pressure are too high to merit the use of conical sections at the end of the shock tube. They also bring out the erroneous time scaling adopted by researchers, particularly when scaling up injury data from rodents to humans is the stated goal of the research. With this in view, since with the conical shock tube we may now have short decay times. This is for free-field blasts in which the long axis of the subject is perpendicular to path of the blast wave and an almost zero effect of the jet (due to very small volume of the driver gas), we can conduct experiments on small animals. With the shock tube positioned vertically and the blast wave traveling downwards, an animal may be placed at the exit of the shock tube on a flange so that the incident wave would impinge the entire body of the animal at once (Figure 12-14). While this positioning is not correct for the case of a shock wave exiting a shock tube as the non-planarities would increase especially at higher pressures. This was not however observed in the conical shock tube as the shock exiting the tube is already spherical and hence, we have a reduced effect of the expansion waves from the periphery catching up with the main shock wave (Figure 13). In experiments that were conducted on the diaphragm-less shock tube earlier at our laboratory, it was observed that mice rarely survived overpressures above 10 psi. However, data from the Bowen's curve (Figure 11) for blast damage on human beings seems to suggest that the mice should be capable of withstanding higher pressures, after accounting for a reduced dosage due to their tiny size [47]. The plateau region occurs at 3 bar overpressure, suggesting that mice should be capable of withstanding this pressure, irrespective of its time scaling to scale down the dosage. The only possible reason why this is happening could be due to the jet of driver gas that follows the shock wave, which is an artifact of a shock tube experiment. Since this is absent in a conical shock tube, we wished to test this using a simple set-up as shown in Figure 14. This data would be very important as it would help in better recreating a war-field scenario to help understand injuries occurring to military personnel.

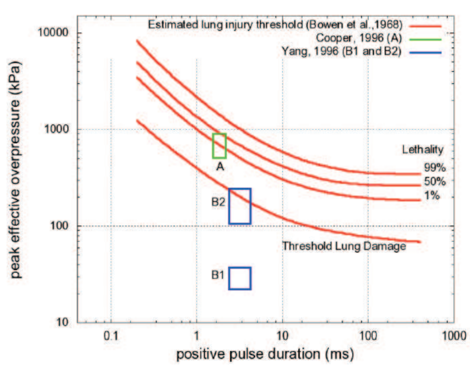


Figure 11: Bowens curves as taken from Courtney and Courtney [47]. This is for free-field blasts in which the long axis of the subject is perpendicular to path of the blast waves

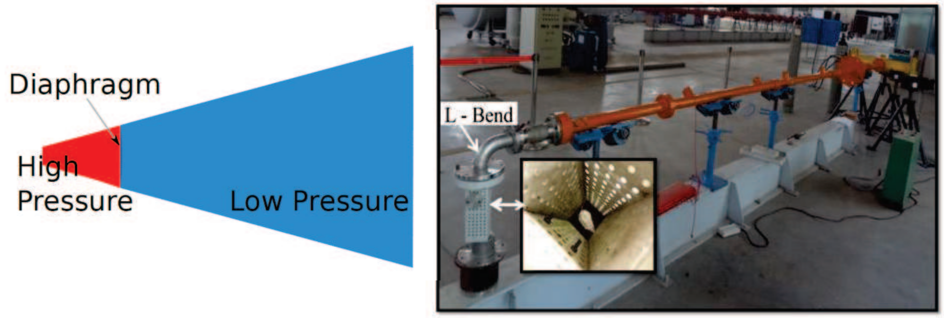


Figure 12. Schematic representation of the conical shock tube concept and its comparison to the conventional diaphragm-less shock tube

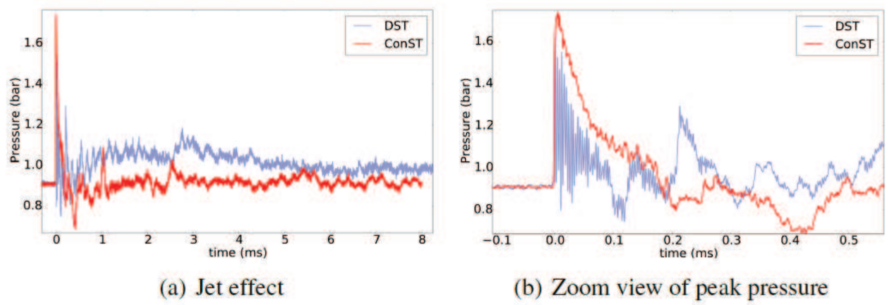


Figure 13: A plot comparing the end pressure signals for the DST and the conical shock tube. The absence of the jet may be clearly seen in (a).

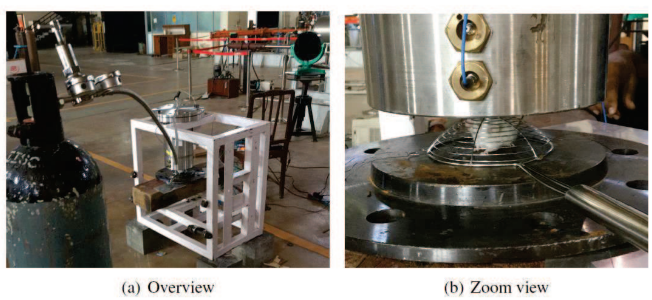


Figure 14: A photograph of the set-up involving the conical shock tube that was used for the mice experiments

Conclusion and author perspective

Shock waves are invariably generated in nature wherever rapid energy transformations take place. Researchers have harnessed the potential of these waves for benefit of mankind. Over the last few decades, numerous applications using shock waves have been developed and many are being developed. Generation and use of controlled shock waves have proved to be an important breakthrough in research. ESWL is the only application that has been translated to clinical practice till now. Although there has been a significant development in the field of shock wave biology, we do not understand the exact mechanisms of these effects. The dependence on the impulse of the shockwave and its co-relation to the efficiency of medical treatment is a topic which requires thorough investigation. Therefore, future research needs to be focused on studying the basic interaction of shockwave with biological systems which would enable us to exploit shock waves to their maximum potential.

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