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History of Shock Waves and Radial Pressure Waves From Newton to Our Times

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Abstract

Although shock waves have been present in nature since its origins, current knowledge took many centuries of study and research. The history of the development of the use of mechanical waves for therapeutic purposes has been a long process in which scientists from many countries contributed. The physical knowledge of waves, the development of generation sources, the first applications in kidney stones and the discovery of their biological impact have been milestones in this long process. The aim of this publication is to highlight previous discoveries that have not been described when analyzing the development of shock waves as a therapeutic tool.

Keywords: Shock waves; Radial pressure waves; History

Shock Waves in Nature

Shock waves are a common phenomenon on Earth and under certain conditions are produced during volcanic eruptions, thunders, the fall of meteors and earthquakes [1].

Despite their presence in nature, these phenomena were not studied until relatively recently. Initially, shock waves were not recognized as such and their research began indirectly from the 17th century when studies were carried out on percussion. Newton published in 1687 "Philosophiae Naturalis Principia Mathematica" [2], considered by many the most influential work of modern science. In this book, the author suggested an explanation of sound propagation based on interparticle percussion in which he developed a basic model of shock waves [1, 2]. Numerous researchers used the model created by Newton to carry out studies in different areas from hydrodynamics to ballistics [1]. This gave rise to a long path of research in which the evolution of knowledge has not been linear but the consequence of the interaction between different disciplines [1].

The aim of this article is to give an overview of the knowledge development process from these origins to the present moment.

Shock Waves Generated by Humans

Krehl [1] states that until the advent of gunpowder, the only way that the human being had to generate shock waves was whip cracking [1]. The crack of a whip is generated by a loop that travels the length of the whip, picking up the speed of sound and creating a sonic boom [3].

The possibility of producing explosions and advances in the study of ballistics led to a greater knowledge regarding shock waves. In 1705, Carré described the effect of a projectile fired against a wooden box containing water, which determined its explosion [1].

The massive use of explosives during the first and second world wars, and the investigations of seismic events led to a greater knowledge of shock waves. The creation of the electrostatic generator (1663) and the Leyden jar (1746) made it possible to accumulate a significant amount of electricity that when abruptly discharged, causes an electrical spark capable of generating shock waves [1]. The electrohydraulic effect was first observed in England by Singer and Crosse in 1815 [1] and later rediscovered in the former Soviet Union by Lew Alexandrovitch Yutkin in 1933. Yutkin, while still a student, poured water onto a plate and then submerged the terminals of two conductors. He turned on the voltage and after a spark occurred, the water shot up and the plate cracked [4]. This phenomenon was called the "electrohydraulic effect" [5]. Using this methodology, he transformed electrical energy into mechanical energy. He developed this idea after observing how lightning could break a log underwater and applied the same principle to plates [6].

A consequence of shock wave passage through fluids is the growth and collapse of bubbles, referred to as acoustic cavitation. In general, it can be produced by an increase in temperature, as in boiling, or by an abrupt decrease in pressure [7]. The phenomenon was discovered at the end of the 19th century

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from the observation of structural damage in steam turbines [1]. It is one of the most important urinary stone pulverization mechanisms during ESWL and has been recognized as a phenomenon that produces both undesirable and desirable biological effects [7-11].

Microbubbles in a fluid (or tissue) near the focal zone of a shock wave generator are compressed by the positive peak of each shock wave. The pressure inside each bubble increases drastically and, after shock wave passage, the high pressure inside it and the trailing negative pulse of the shock wave, cause a fast bubble growth. Each bubble increases its volume hundreds of times and, a few hundred microseconds later, collapses violently. Generally, the collapse is asymmetric, generating a high-speed microjet of fluid that tunnels through the bubble [7]. The collision between the inward-moving wall of each bubble and the microjet produces secondary shock waves.

It has been reported that radial pressure waves also generate cavitation phenomena [12].

Effect of Shock Waves on Living Beings

The effect of physical stimuli on life begins with its very origin. The first molecules evolved into vital forms in the ancestral oceans, when the right conditions of pressure and temperature were created [13]. However, the effect of mechanical forces on living beings was unknown for a long time. Recognizing the influence of mechanical forces has been a result of lengthy observations, study, and research over time.

Today, it is clear that cells respond to mechanical stimulation activating specific signaling pathways and genes, allowing them to adapt to their dynamic physical environment [14].

The first observations were made at the beginning of the 20th century. It has often been said that the effect of shock waves on human tissue and organs was first discovered during World War II, but in fact, the first observations were made during World War I [15]. Augusta Déjerine-Klumpke is considered the first female neuroanatomist, who, together with her husband (a famous French neurologist) wrote one of the masterpieces of neuroanatomy [16]. At the end of the First World War, Déjerine-Klumpke carried out a radiological study of the amputation stumps of those wounded in combat with poor surgical results [15]. She discovered that in the majority of failed cases, a heterotopic ossification phenomenon occurred. She deduced that in addition to the shrapnel, there was another factor that had influenced the healing process. This factor was the effect of shock waves on soft tissues [15]. Her studies were cut short due to the end of the war.

During and after the Second World War, there was great interest in the subject. The first observations were damage to lung tissue in tank personnel, after exposure to a blast hitting the tank [17, 18]. This is now defined as primary blast lung injury resulting from exposure to an explosive shock wave [19, 20]. The lungs are not the only tissues to be affected; injuries can also affect other gas-containing organs such as the larynx, middle ear, and bowel. Cerebral edema, vascular endothelial injuries, testicular ruptures, liver, and splenic lacerations have also been reported [21]. After Second World War, a vast amount of animal research was undertaken confirming these findings [22, 23]. These effects have also been reported as complications of lithotripsy [24, 25].

At Dornier aerospace company, Germany, during the late 1960s and early 1970s, the effect of shock waves on solid material was intensively studied. At that time, Dornier was an aircraft manufacturer concerned with supersonic aircraft dents and erosions caused by rain and micrometeorites [6, 26]. Experiments with small high-speed projectiles in the early 1960s by engineers at Dornier revealed that pain similar to an electric discharge was felt when touching the target at the moment of projectile impact [6, 7].

From 1968 to 1971, the German Defense Department studied the interaction between shock waves and biological tissue on animals [6, 26, 27].

First Therapeutic Applications of Shock Waves

The first therapeutic proposals for shock waves were based on their mechanical properties and came from the field of seismography. Frank Rieber, an American visionary, inventor and geophysics expert, was the first to model seismic wave patterns [28]. In 1947, he patented a device that he called "shock wave generator" and proposed the possibility of treating brain tumors by applying shock waves. This study failed to go beyond theory as unfortunately, the patent did not survive long enough for the shock wave treatments to be completed [28]. Many consider Rieber's patent was the start of the medical specialty known as extracorporeal shock wave lithotripsy.

Three years later in the Soviet Union (1950), Yutkin patented the principle of shock waves in the disintegration of kidney stones using an endoscopic electro-hydraulic generator [6]. He was considered out of favor with the Stalinist government and was banished, so the use of his invention was delayed for at least 10 years [29]. The device called URAT-1 was designed to comminute bladder stones using shock waves produced by electric discharges between two electrodes located at the tip of an endoscope [7].

During the 50s, different researchers tried to destroy calcareous deposits by means of sound, but these studies did not come to fruition due to some additional tissue damage [7].

William P. Mulvaney was the first person who attempted to disintegrate stones through "ultrasonic vibrations," in 1953 [30, 31].

The first electrohydraulic lithotripsy was performed in 1959 by Goldberg at the Urological Department of the Municipal Hospital in Riga (Republic of Latvia) following Yutkin's instructions [6, 32].

In 1971, Haeusler and Kiefer reported the first in vitro disintegration of a kidney stone using shock waves produced by high-speed (up 2000 m/s) water drops [6, 7, 33].

In 1974, the first experimental phase of research including in vivo and in vitro effects of shock waves was conducted by Chaussy et al., [26]. The first shock wave lithotripter (TM1) was developed.

From 1975, studies with small animals were initiated [26]. Lung damage was reported [23, 26, 34]. A model to implant human kidney stones into the renal pelvis of dogs was created [26, 35]. From 1976 to 1978, the project was on the verge of being abandoned, but fortunately encouraging results made it possible to obtain new funds [26]. Chaussy and colleagues demonstrated the possibility of fragmenting the stones and it was verified that no significant damage was produced in the renal parenchyma of the dogs subjected to the application of shock waves [26].

Due to difficulties with ultrasound localization, a three-dimensional X-ray system was integrated into the device. During 1979, reduction of kidney function as a result of shock wave exposure was excluded by nuclear medicine methods and laboratory tests [26].

The first Human Model clinical lithotripter (HM 1), manufactured by Dornier, was installed in Ludwig-Maximilians University, Klinikum Grosshadern, Munich [26, 36, 37]. On Thursday, February 7, 1980, the first extracorporeal lithotripsy was carried out by Chaussy et al., [6, 26, 37-39]. Not only was this the first successful case, it was also the first report of a complication as the patient suffered extrasystoles [6, 26]. Follow-up showed passage of the fragments without complications [26]. That same year, the first report of a series of cases was published [39]. The United States Food and Drugs Administratio (FDA) granted pre-market approval in the United States in 1984 [7], and the first lithotripsy center was opened in that country that same year in Indianapolis [6, 26].

Piezoelectric shock wave sources were developed in 1978 by the company Richard Wolf GmbH [7].

The design of an electromagnetic pressure wave source was published in the beginning of the 1960s by Wolfgang Eisenmenger, yet electromagnetic lithotripters were not developed until the beginning of the 1980s [7]. The first successful treatment with an electromagnetic lithotripter, developed by Siemens, was performed in Germany 1986 [7]. After 1985 stones in other organs, such as the gallbladder, bile duct, pancreas and salivary glands, were also treated with shock waves [40].

Discovery of Biological Effects and Mechanotransduction

The therapeutic use of shock waves is an excellent example of the impact that mechanical forces have on living cells and tissues. However, coming to an explanation of the mechanism of action took many years. The development of mechanobiology is deeply linked to the interpretation of the mechanism of action of shock waves and radial pressure waves. The field of mechanobiology has grown dramatically in the past decade; however, its principles were initially studied nearly 100 years ago.

In 1892, Wolff proposed what was later popularized as Wolff's law [41]. He postulated that the orientation of the bone trabeculae is determined by the action of mechanical loads on the bone [41]. Although the validity of this theory is disputed today, it was one of the first approaches to the interaction between mechanical forces and biology.

A few years later, D'Arcy Thompson, in his work "On Growth and Form," published in 1917, first postulated his thesis that biological form can reflect physical and mathematical principles [42]. In the reissue of the abridged version of 1992, Bonner stated that genetics by itself is not enough to generate forms, and that interactions with physical processes are necessary [43, 44].

The effects of mechanical forces at the cellular level only drew major attention in the 1950s, when it was first shown that cancer cells can grow in soft agar in an anchorage-independent manner, whereas most non-cancerous cells cannot [45]. Since then, countless research has shown that cells are not only able to sense biochemical stimuli but also physical ones as force, geometry, and matrix elasticity [46]. Fung, considered the father of biomechanics, proposed in the 60s that mechanical stress could have substantial impacts on remodeling and growth of living tissues [47].

In the 70s, the multiproteins structures that provide mechanical links to the extracellular matrix were discovered. These structures enables inside-out and outside-in mechanosignaling. Integrin-based adhesion complexes, which are closely associated with the actin cytoskeleton, are able to recognize the biochemical factors of the extracellular surroundings including their physical and geometrical characteristics [46]. The mechanical information arising from modifications of the extracellular matrix detected by the multiprotein complexes under the membrane and propagated at the cytoskeleton level. Impacts on proteins located at the membrane or in the cytoplasm induce their structural modification and subsequent shuttling to the nucleus [48].

The ability of cells to translate mechanical forces and deformations into electrical and biochemical signals was named mechanotransduction [49, 50].

During the 80s and the 90s, there was increasing evidence of the interaction between physical forces and biology, but strikingly the idea of using shock waves to treat indications other than lithotripsy emerged after incidental observations of a shock wave-induced osteogenic response on living tissue in vivo [51]. During the 1980s, urologists who performed radiographic monitoring of lithotripsy treatments noted osteoproductive phenomena that could not be explained by a simple mechanical effect. This led Haupt to investigate the effect of waves on skin lesions and fractures with very encouraging results, marking the beginning of the use of shock waves in musculoskeletal pathologies [52, 53, 54].

At the beginning of the 21st century, Wang et al. [55] demonstrated that shock waves induce osteogenesis and neovascularization at the tendon-bone junction associated with the early release of angiogenesis-mediating growth and proliferating factors leading to improvement of blood supply and tissue regeneration [56].

The same author proposed in 2003 the well know model of a cascade interaction between physical shock wave energy and biologic responses [18].

Brañes et al. [57] demonstrated in 2012 that ESWT is associated with increased neovascularization and neolymphangiogenesis in rotator cuff tendinopathy.

The discovery of the release of proangiogenic exosomes after the application of shock waves in ischemic cardiac muscle tissue has been another important step in understanding the mechanisms of action of shock waves [58].

Therapeutic use of Shock Waves in Musculoskeletal Injuries

Gloeck [59] and Horn [60] report that the first treatment attempt in the fields of orthopedics was made by Karpman et al. in 1987 [61, 62]. He tried to break the bone cement mantle that fixed a hip implant before revision surgery.

However, Valchanou claims that his team was the first to use shock waves to treat non-unions in 1986 [63, 64, 65]. Ten voluntary patients, military men from the Bulgarian army, were exposed to the effect of shock waves using a Dornier device, from May to July 1986, at the High Military Medical Institute Sofia, in Bulgaria. The authors developed what they called the "Stereorestorer" designed and made in the factory Electron-Varna, Bulgaria in 1986–1987and applied for the patent in the United States in 1988. It was finally approved with the number 4979501 as "Method and Apparatus for Medical Treatment of the Pathological State of Bones" with date December 25, 1990 [65]. The first presentation of the results was on May 23, 1988, at the American-Bulgarian Congress on Arm-Surgery in Albena, Bulgaria. It was also presented on the 7th Int. Congress on Endo-urology in November 1989 in Kioto, Japan [63]. In 1991, the Bulgarian authors published their experience and more research would follow on the treatment of non-unions by a variety of scientific researchers [64].

In 1995, Haist reported the highest rate of consolidation in hypertrophic non-unions which was 100% compared to 23% in atrophic ones [66].

Haupt reported in 1992 and 1997 the results using a fracture model in rats [40, 54]. In the early 90s, Dahmen et al. first used shock waves for the treatment of soft tissue pain in proximity to bones [67-69]. In 1992, Dahmen et al. published the first results of the therapeutic use of shock waves in shoulder pathology [67]. One year later, Loew and Jurgowski published their initial experience with the use of shock waves in rotator cuff calcifications in five patients [70]. This was followed by a publication in 1995 including 20 patients [71] and other prospective study published in 1999, including 190 patients divided into a control group and different treatment alternatives with shock waves [72]. Haupt and Katzmeier treated 29 patients, of whom 14 became pain-free and 10 were substantially improved [73].

The interest in the therapeutic effects was not limited to Europe. In 1998, Spindler et al. from Tucumán, Argentina, published their first results in the treatment of rotator cuff calcifications in the Journal of Rheumatology [74].

Rompe et al. reported good or excellent outcome in 48% and acceptable results in 42% at 24 weeks in 50 patients with chronic tennis elbow treated with shock waves in 1996 [75].

Good results were also reported in plantar fasciitis. In 1996, Rompe et al. published a randomized and prospective study carried out over a 2-year period in which they found statistically significant results between the treated groups and those that did not receive shock waves [76]. Two years later, Perlick et al. reported after 12-week and 12-month follow-ups that 51 of 83 patients became pain-free and 20 patients improved from the treatment [77].

In a consensus meeting in 1995, instructions were established for the use of extracorporeal shock waves in musculoskeletal indications: (a) High energy only, (b) small "focus," (c) anesthesia, (d) imaging-guided application, (e) avoiding growth plates, (f) no acute injuries, (g) soft-tissue pain in the proximity to bones (insertional tendinopathy), and (h) tendinopathies with extraosseous calcification [40, 78].

Based on the promising results of the first experiences in the area of orthopedics and traumatology, other specific devices for musculoskeletal pathology were introduced into the market. These devices focused the shock waves to a focal point of approximately 4–6 cm deep from the application site on the skin. The first known commercial focused shock wave device of this type, called OssaTron, was introduced to the market in 1993 [7]. The Food and Drugs Administration approved therapy with the OssaTron device for chronic plantar fasciitis in 2002 and for tennis elbow in 2003 [7].

Since 1999, devices featuring ballistic pressure waves were introduced in the market [7, 79]. These waves are produced mechanically by a compressed air driven projectile which hits the applicator. This technology has been referred to by many different terms, such as radial shock wave therapy, extracorporeal pulse activation therapy, radial pressure wave therapy, and radial ESWT. Strictly speaking these devices generate radial pressure waves, not shock waves [7, 38, 80]. Compared to focused shock wave generators, which produce shockwaves at the focus of the device, radial "shock wave" generators emit pressure waves with a lower peak positive pressure and much longer rise times. Some radial pressure wave sources have applicators that can slightly focus the pressure field, generating even more confusion among users. The fact that they are different from a physical point of view does not mean that both techniques do not share indications; however, there are also indications specific to each method.

Final Remarks

The history of the development of the use of mechanical waves for therapeutic purposes has been a long process in which scientists from many countries contributed (Fig. 1).

From the first reports, there has been a great diffusion of the use of shock waves in musculoskeletal pathology. In many countries, the use of shock waves to treat musculoskeletal diseases has outscored the number of urological indications [7].

Although the results of the treatment in certain orthopedic pathologies are undeniable, it is still necessary to support the indications with studies with a high level of evidence. This is the necessary final step to achieve the massive incorporation of this fascinating technology into the therapeutic armamentarium.

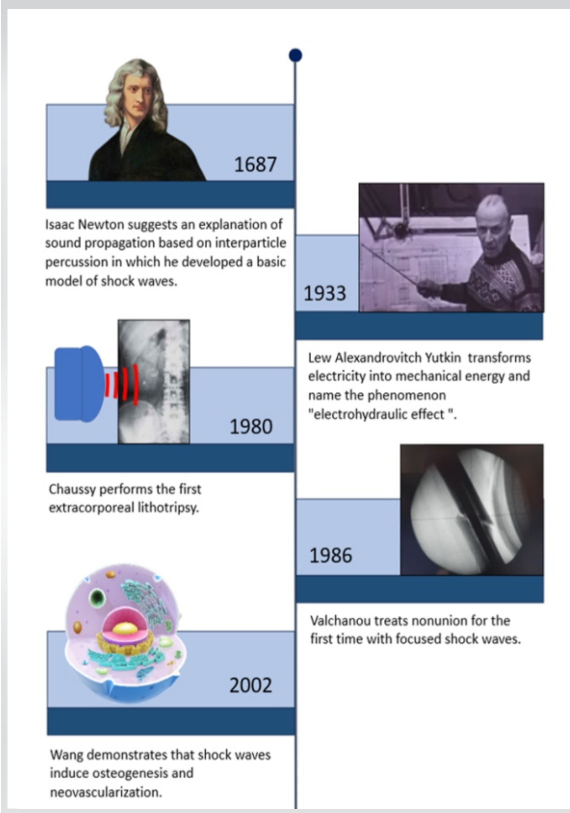

Figure 1: Timeline highlighting the main milestones in the development of shock.

Declaration of patient consent: The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has/her given his/her consent for his/her images and other clinical information to be reported in the Journal. The patient understands that his/her name and initials will not be published, and due efforts will be made to conceal his identity, but anonymity cannot be guaranteed.

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