HIGH ENERGY SHOCKWAVE AND ITS APPLICATIONS IN ORTHOPAEDICS

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Abstract: Shockwave is characterized by its high instantaneous acoustic energy delivered in a short duration of time when it reaches an interface between materials of greatly different acoustic impedance. Extracorporeal shockwave therapy (ESWT) is used in non-surgical removal of kidney stone by targeting the shockwave over it. The acoustic energy so dissipated would disintegrate the stone to facilitate its removal through the urinary tract. ESWT has recently been drawing more attention in orthopaedics and rehabilitation. Its applications include treatment of bone fracture healing. The shockwave machine (Sonocur Plus, Siemens) used in this study was able to deliver a peak acoustic pressure in the range of 30 MPa within a short duration of microseconds. Biological specimens (porcine humeral head, rib bone and rabbit tibia) were used. After the application of shockwave, we found on the porcine specimens hair-line cracks along the direction of the rib bone and minute chips of diameter of about 1-2 mm over the surface of the articular cartilage at the exact location where the shockwave was focused. When shockwave was applied to rabbit's tibia at a low intensity, there was no visible change over the skin, muscle and bone. When the intensity was increased to a median level, there was haematoma observed at the focal area. When shockwave of maximum intensity had been applied, there was obvious haematoma at the treatment site. Microfractures with a length of 10 – 400 μm were observed at the ESWT treated site of the tibial bone. We believed that the application of high energy shockwave can be targeted at the precise treatment site causing microfractures. This microfracture may be helpful to initiate bone fracture healing in delayed and nonunion conditions.

Introduction

A shock wave is an acoustic wave characterized by high instaneous acoustic pressure delivered to the maximum value within a few nanoseconds [2]. Shockwaves were originally applied in breaking up and destroying stones in the renal or biliary tract, and salivary gland in clinical practice [4]. The typical form of shockwave includes a sharp positive rise in pressure in nanoseconds, followed by a gentle and variable negative pressure over microseconds (Figure 1) [1]

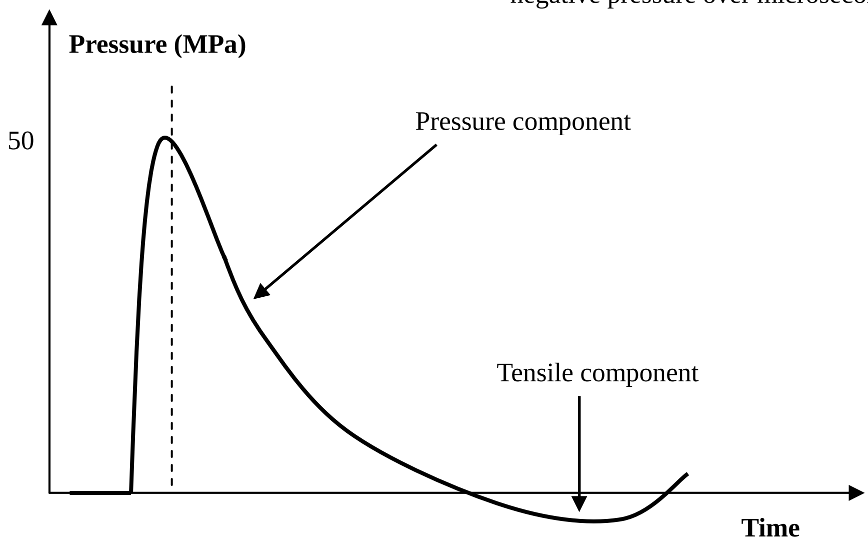

Figure 1: Typical waveform of shockwave.

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A focal area of the shockwave is defined as the area in which 80% of the maximum energy is reached. Energy flux density is the term used to describe the shock wave energy flows through an area perpendicular to the direction of propagation [2]. It can be expressed in the following formula (1) and is measured in millijoule (mJ) per millimeter square (mm [2]).

$$\text{Energy Flux Density} = dE / dA \qquad (1)$$

E – energy of shock wave at a particular location

A – area in which the shock wave is existent

According to Rompe, the energy levels can be divided into low, medium and high [2]. Shock waves of different energy levels will cause different effects inside the body. They are summarized in figure 2.

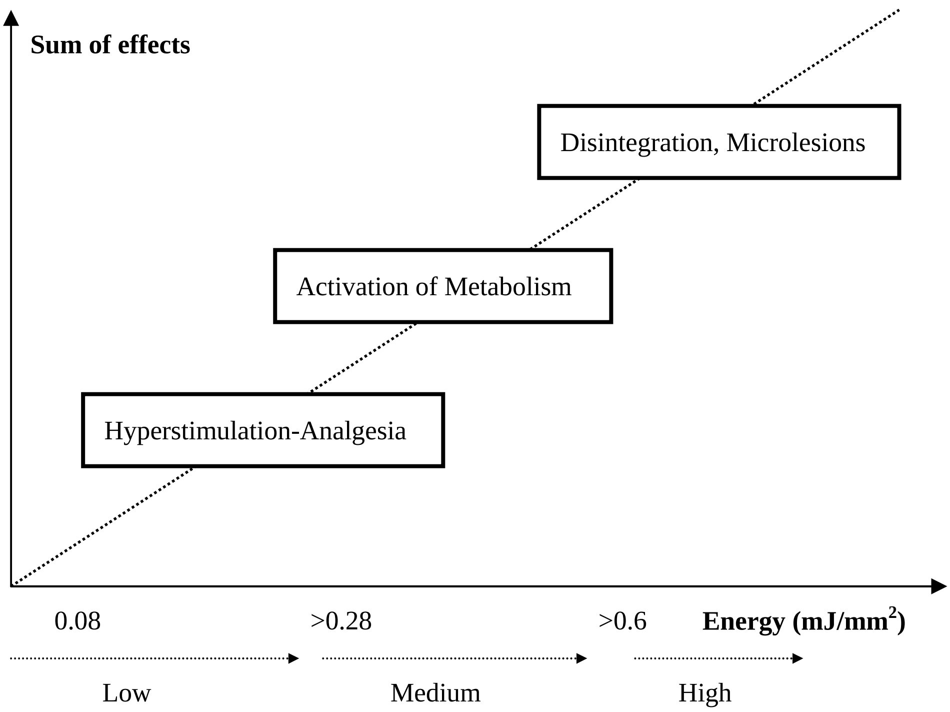

Figure 2: Biologic effects of shockwaves at different energy levels.

The body includes various tissues which have different degrees of elasticity and compressibility, and affect the propagation speed of sonic waves. When a shockwave enters the body, transmission through and reflection from different media occurs due to their different acoustic impedance: (water 1.49; muscle 1.72; fat 1.37; cortical bone 7.38; renal stone 6.25) [1]. As cortical bone and renal stone have similarly high acoustic impedance values, it is believed that shockwaves cause microfractures to bone in a similar manner as the disintegration of renal stones. Ogden *et al* [1] reported that the intensity of a shockwave transmitted into cortical bone is about 65% of incident intensity, causing a strong interaction at the periosteal interface. The cavitation effect also causes partial osteocyte death, followed by the migration of osteoblasts to the non-union site for local new bone formation.

The effectiveness of extracorporeal shockwave therapy (ESWT) on healing non-unions has been demonstrated in some clinical studies. Wang *et al* reported a success rate of 80% in 12 months with the application of 6,000 impulses at 28 kV to hypertrophic non-unions [5]. Schaden *et al* reported a healing rate of 75.7% in 18 months following 12,000 impulses at 28 kV [3]. Rompe *et al* also reported that 72% of patients showed bony consolidation after a single shockwave treatment [2]. None of these studies showed any discernable side effects after shockwave treatment.

Those previous reports generated an idea that shockwave can be used as a treatment modality in the conditions of fracture non-unions.

The following is the report on two experiments with non-human bone and specimens to demonstrate the direct effect of shockwave on bone and its implication to the fracture healing.

Methods

Four pieces each of fresh porcine humeral head and rib bones were used. Before the treatment on every specimen, the muscle and soft tissue were removed. The specimen was fixed on plaster of Paris which set into a block when mixed with water. Distilled water was used as the transmission medium. The application of shockwave was applied and guided by an in-line ultrasound scanner. This was to ensure that the shockwave was focused at the articular surface of the humeral head and the cortical bone of the rib. Shockwave of energy flux density of 0.54 mJ/mm [2] was applied at a rate of 1 pulse per second for a total of 1000 pulses. Immediately, after the treatment, the bone and joint surfaces were examined through a dissection microscope (10x) immediately for any structural change over the surface.

In another experiment, twelve mature female New Zealand White rabbits of 18 weeks of age with an average body weight of 3.2 kg (2.7-3.8 kg) were used. They were divided into three groups for single application of ESWT in low energy level (0.23 mJ/mm [2]), medium energy level (0.37 mJ/mm [2]) and high energy level (0.54 mJ/mm [2]). A SONOCUR Plus (Siemens, Erlangen, Germany) shock wave generator was used for the treatment. Before the treatment, the rabbits were sedated by anesthesia with a mixture of 0.9 ml xylazine and 0.6 ml ketamine. The hair was shaved around the treatment site. The rabbits were positioned on the bench in such a way as to keep the medial shaft of tibia at the center of the focus during the application of ESWT. Transmission gel (Chattanooga Group Inc, TN, USA) was used as a coupling medium between the shock wave generator and the skin. One thousand shock waves at a rate of 1 pulse per second at a power setting of 0.54 mJ/mm [2] were applied at the mid-shaft of the tibia (Figure 3). Observation for the skin condition was done immediately after the application of ESWT and those rabbits were sacrificed 7 days after the treatment for tissue processing. The specimens were examined under scanning electronic microscope (SEM).

Results

On the porcine specimens, hair-line cracks were observed along the direction of the rib bone and minute chips of diameter of about 1-2 mm were observed over the surface of the articular cartilage at the exact location where the shockwave was focused. Such surface destruction was much reduced or not observed when the shockwave was focused away from the cartilage and bone surface, or when its dosage was reduced.

For another experiment, shockwave was applied to the rabbits' tibiae at a low, medium and high intensity. In case of the low intensity treatment, there was no visible change over the skin, muscle and bone in all the 4 rabbits after treatment. When the intensity was increased to a medium level for another group of rabbits, there was a slight haematoma presented at the focal area. The temperature was slightly increased around the treatment site when palpated. When shockwave of high intensity was applied to the third group of rabbits, there was a larger area of haematoma with a greater increase of temperature around the treatment site. Those haematoma was recovered within 2-3 days after the treatment. All the rabbits could walk normally after the ESWT.

We could not find any crack or microfracture in the microscopic image of the low and medium shockwave treatment groups. However, in the high energy level group, microfractures of a length of 10 – 400 μm was found in the slides located at the shockwave treated site of the bone (Figure 4). In some cases, bone resorption along the microfractures occurred. The microfractures and bone resorption were confined in an area of 3 mm [2].

Conclusions

From the above results, we believed that the application of shockwave can be confined to a small focus of definite size (in area and depth) for initiating the microcracks to the bone structure. If shockwave is to be targeted at a precise treatment site, suitable guiding device such as an in-line ultrasound scanner would be needed for accurate location. It is also important for the therapists to identify and locate the treatment site precisely in order to achieve the expected therapeutic effect. On the other hand, therapists should avoid potential destruction to the bone or joint by suitably limiting the dosage of ESWT or by preventing it from being focused right over the cartilage or bone surface. High energy ESWT can result in microfractures, initiating subsequent bone remodeling in a confined area of the bone. Use can be made of this effect to promote healing of bone fractures with non-union or delayed union.

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Figure 3: Application of ESWT to the tibia of the rabbit under general anesthesia.

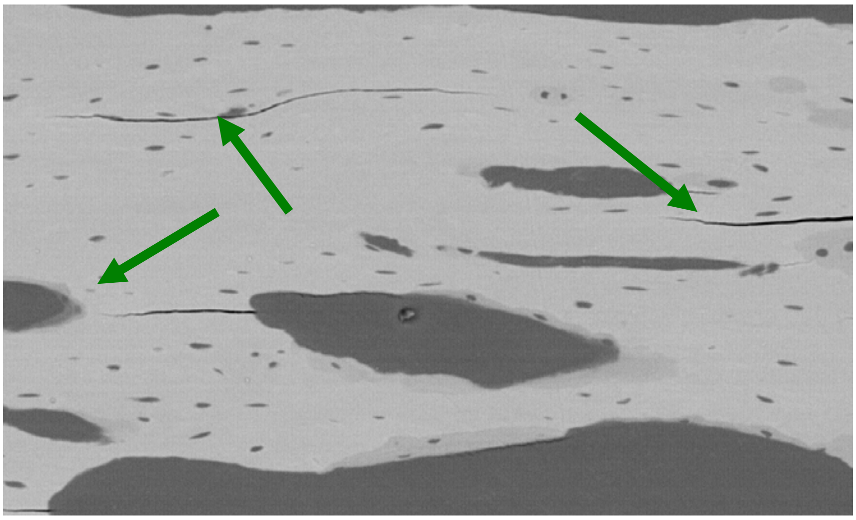

Figure 4: SEM on the section of rabbit tibia. Lines of cracks (labeled in arrows) were observed after the shockwave treatment. Magnification = 500x.

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