Nonlinear Shock Wave Propagation in Soft Tissues as a Mechanism of Injury

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Abstract

The aim of this study is to investigate the propagation of shock waves and self-preserving waves in soft tissues such as aorta and brain as a mechanism of injury in high-rate loading conditions as seen in blunt trauma and blast-induced trauma (BIT). It is shown that such phenomena can only be seen in nonlinear viscoelastic materials and the existing linear and quasi-linear models predict only decaying waves. Various attempts to explain the mechanisms of soft tissue injuries such as traumatic aortic rupture (TAR) and traumatic brain injury (TBI) as a result of car accidents and sports injuries have been reported over the past 3 decades. In recent years, with advances in protective gears, blast induced trauma (BIT) has also become a major concern. To date, the mechanisms of soft tissue injuries, especially at high-rate loadings, are not still clearly understood.

As a blast wave enters a biological tissue, high-rate stress waves, which have longitudinal and shear components, develop in the tissue and such components can have devastating effects on the tissue based on the amplitudes of the waves and the orientation of tissue fibers. In this study, nonlinear viscoelastic wave propagation in soft tissues is studied and a criterion for the development of one-dimensional shock waves has been proposed as a mechanism of injury.

Theoretical Background

Hyperelastic Model

Generalized Mooney-Rivlin model was used (6 terms)

\[ W = \sum_{p,q=0}^{N} C_{pq} (J_1^{-3})^p (J_2-3)^q \]

where \( W \) is the strain energy function, \( J_1 \) and \( J_2 \) are the first and second invariants of the right Cauchy-Green deformation tensor, respectively, \( C_{pq} \) are the Mooney-Rivlin's elastic coefficients derived from instantaneous elastic response and the steady-state response is very similar to the experimental data in the form of generalized Mooney-Rivlin hyperelastic solid. In the above equations, \( a \), acts as the critical amplitude and is a material constant. This means that for a given material, there exists a critical amplitude, which determines that when a discontinuous wave enters the material, which is a characteristic of blast waves, whether the wave will be damped and dissipated or continue as an acceleration wave with constant amplitude or even become a shock wave, in which case it can have devastating effects on the tissue in terms of injury.

Results

As shown in Fig. 2, the ratio between the instantaneous elastic response and the steady-state response is very close to constant and therefore the QLY is an acceptable material assumption. Otherwise, two separate functions were required for instantaneous and steady-state responses. The value of the discontinuity in acceleration plays a significant role in determining whether a shock wave will form or be damped (Fig. 5).

Conclusions

A novel method has been used in order to determine the material parameters. In this model, the elastic coefficients were derived from isochronous curves. This eliminates the need for any physical data fitting. Based on the equations above, we can see that the initial value of the discontinuity in acceleration plays a significant role in determining whether a shock wave will form or be damped (Fig. 5).

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References