Dynamic Response Characteristics of an Ocular Model under Shock Waves

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Abstract

With the widespread use of explosives in modern warfare and civilian industrial activities, blast-related ocular injuries have become increasingly common(Han, 2022; Wong et al., 2000). On one hand, high-velocity projectiles generated by explosions can cause various structural damages, including corneal edema, hyphema, lens dislocation, and retinal tears(Sukati, 2012). On the other hand, due to the intricate and delicate anatomy of the eye, blast shock waves can still penetrate ocular protection and propagate inside the globe even when external foreign bodies or fragments are intercepted, thereby inducing injury to intraocular tissues(Rossi et al., 2012). At present, the dynamic propagation mechanism of shock waves within the eye is not yet fully understood, and corresponding biomechanical injury thresholds have not been clearly established. These limitations constrain the development of effective eye protection against blast loading and hinder post-injury diagnosis and treatment.

In this study, a biomimetic eye–orbit physical loading model was constructed based on the anatomical geometry of the human globe–orbit complex and the mechanical properties of the relevant tissues, using hydrogel materials and 3D printing technology. The model was mounted in a double-diaphragm shock tube as Figure 1 shown, where graded loading tests were conducted by adjusting the shock wave overpressure, and the macroscopic deformation response under different loading intensities were recorded. On this basis, a finite element model of the human eye was developed, incorporating key structures such as the cornea-sclera shell, ciliary body, lens, vitreous body, and retina as Figure 3(a). The experimentally obtained pressure-time histories were applied as boundary conditions to compute the stress-strain distributions within each intraocular tissue under different overpressure levels. The high-speed camera results indicate that, following shock wave loading, the globe exhibits a characteristic “compression–rebound–oscillation” dynamic response(Delori et al., 1969) as Figure 2. As the peak

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overpressure increases, the maximum deformation amplitude of the globe grows significantly, the duration of the rebound and oscillation phases is prolonged, and the severity of surface wear on the model becomes more pronounced. Finite element simulations further show that, at shock wave arrival, the cornea, as the first-loaded structure, experiences pronounced stress concentration as Figure 3(b); subsequently, due to the low compressibility of the lens and intraocular media, the intraocular pressure rises rapidly, and the pressure wave propagates posteriorly along the anteroposterior axis, sequentially affecting the lens and retina. Different ocular structures exhibit distinct stress and strain responses, thereby characterizing the dynamic mechanical response behavior of the ocular model under shock wave loading.

This study was based on the bionic obrit-eyeball model constructed in the laboratory, conducted experiments using a shock tube to simulate the equivalent explosion shock wave and carried out parametric simulation calculations, systematically analyzed the dynamic response and damage characteristics of the eye tissue. However, due to the complexity of the internal structure of the eye and the complexity of the physiological environment, the current model is still unable to fully replicate all the damage patterns caused by real explosive impacts. In addition, inter-individual variability in ocular anatomy and biomechanical properties may lead to disparities between modeled and actual injury patterns. Moreover, because real human eye specimens are difficult to obtain, the present model still relies on certain idealized assumptions regarding material properties, structural layering, and boundary conditions. To further enhance biological fidelity and predictive capability, future work will focus on developing higher-fidelity physical and numerical eye models, using multi-material 3D printing and hydrogel-based biomimetic techniques to more accurately reproduce the mechanical behavior of intraocular tissues, and establishing multiscale coupled biomechanical–pathological models to elucidate the internal mechanisms linking shock loading, tissue deformation, and clinical pathological manifestations in a systematic manner.

Keywords: ocular injury; blast shock wave; biomechanics; finite element analysis; injury criterion

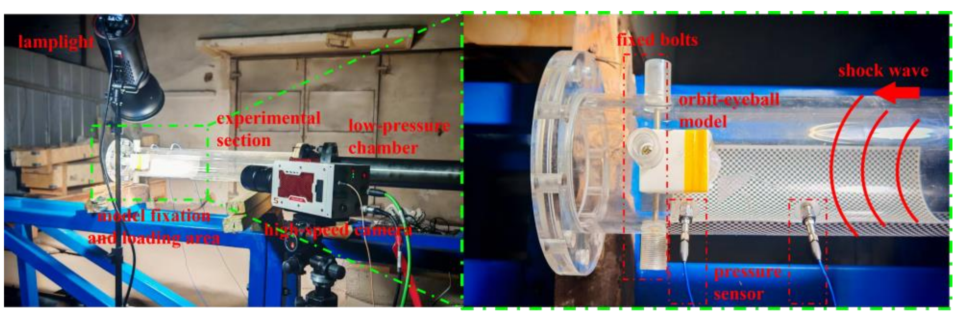

Figure 1: Shock tube experimental setup diagram

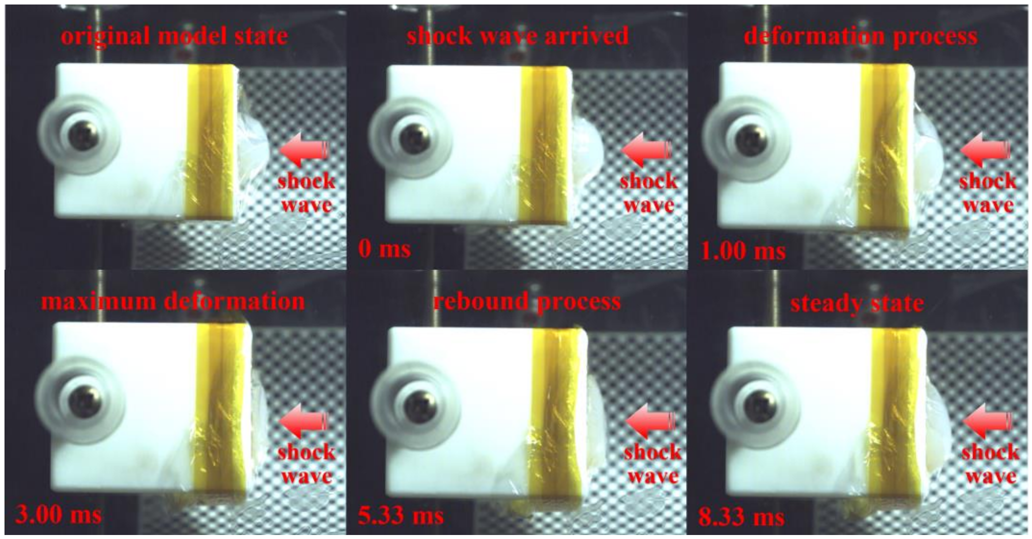

Figure 2: Orbit-eyeball model under shock wave loading recorded by high-speed photography

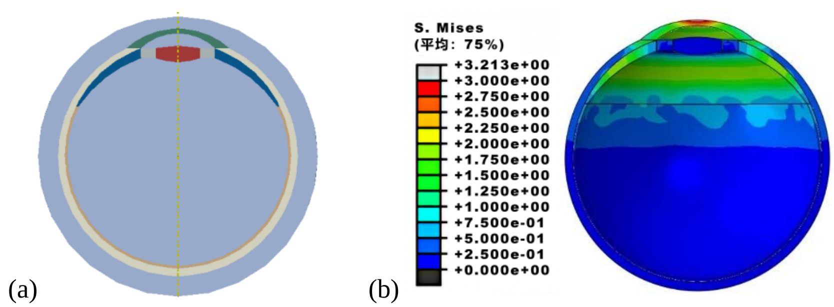

Figure 3: (a) Finite element model of the eyeball and (b) simulation of the eyeball under shock wave action

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