MEANINGFUL CONCEPTS OF HEAD INJURY CRITERIA

by

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ABSTRACT

Current head injury tolerance parameters or criteria used for regulation involve linear acceleration levels or their histories for the entire cranium. Other proposed criteria pertain to angular acceleration, or a mean strain; a viscous criterion has been proposed for soft tissue. Such prescriptions are unable to differentiate between various regions of the head. Also, except for strain, the other parameters do not directly produce trauma and can thus at best only be indirectly related to trauma. It is important to devise a methodology that will permit the stipulation of loading limits of individual tissue using accepted engineering failure parameters for physical disruption and, concomitantly, a proportionately lower limit for physiological dysfunction. This contribution intends to outline such a procedure based on the principles of continuum mechanics and knowledge of material properties. It represents a further development of the suggestion of the author 23 years ago to analyze head response to impact by means of these analytical tools. An example of the response to impact of a viscoelastic tube which could be extended to model the loading of a cerebral vessel due to a head collision is indicated.

INTRODUCTION

History

Rational closed head injury research was started experimentally at Wayne State University in the 1940's (Gurdjian, 1975) and in terms of physical models and processes by Holbourn (1943). Since that time, numerous studies have been conducted that can be classified as (1) Epidemiological information, (2) Testing of head tissues to determine their mechanical response to loading, (3) Experiments designed to obtain physical results of controlled head impacts on living human surrogates (such as human cadavers), live and sacrificed animals, inanimate replicas such as anthropometric dummies and other structures, (4) Analytical modeling of cranial collisions based on the principles of rigid-body or continuum mechanics (5) Digital computer solutions of prescribed head injury scenarios, and (6) Cross-correlation of information including scaling to develop a relation between applied load and resultant trauma, and to provide criteria for a specified amount of damage. This damage has generally been lumped into an Abbreviated Injury Scale (AIS) with numerical values spanning no or minor injury to certain fatality.

Head Injury Acceleration Criteria

The objectives of (6) are still intensively occupying those charged with the reduction, diagnosis and/or management of cranial trauma. The first quantitative attempt to define the boundary of acceptable injury to the head resulted in the Wayne State Tolerance Curve (WSIC) (Lissner, 1960, Gurdjian, 1962) which separated tolerable from dangerous or fatal domains by an acceleration-time curve which was subsequently modified a number of times. It was based on the observed onset of skull fracture, hypothesized to correspond to the initiation of concussion, in cadaver drops for impact durations ranging from 1-6 ms. This criterion made no distinction between skull fracture and brain damage, nor did it differentiate with respect to location and direction of the blow. All subsequent head injury criteria, such as the Severity Index (SI) (Gadd, 1966) and the Head Injury Criterion (HIC) (Versace, 1971) exhibit the same limitations; they specify upper bounds of the acceleration or of functionals of its history. This has also permeated the regulations of government agencies charged with overseeing the testing of motor vehicle components or ATD's and certifying safety devices such as motorcyle helmets.

Other models of head injury were also proposed (1971 Stapp Conference); the most important addition or alternative is the consideration of angular acceleration (Ommaya, 1966). The history of this subject is very well documented, for example, by Hess et al. (1980, 1983), supplemented by the periodic SAE Information Reports (1988). One attempt has been reported to combine linear and angular acceleration into a single criterion encompassing both kinematic parameters (Newman, 1986).

The appeal of using linear acceleration or a functional therof as a criterion is evident: It is relatively easily measured at a specified point of the subject, usually the center of gravity of a surrogate. It also fits neatly with Newton's second law of motion, which is a much simpler basis for analysis than the equations of motion for a deformable body. In turn, the human head is often modeled as rigid, when it, or at least the contents of the skull, definitely should not be so regarded.

Disadvantage of a Single - Valued Criterion

It is worth reporting that the results of substantial experimentation on primates and human cadaveric material (Ono, 1980), interpreted by the methods of Stalnaker et al. (1973; 1985), quantitatively corroborated the Wayne State Tolerance curve for the onset of concussion, but also provided evidence that the head could sustain approximately twice this dosage for the onset of skull fracture. These conclusions provide clear experimental documentation that the use of a single numerical value, i.e. an acceleration level and duration, the SI or the HIC, cannot distinguish between tolerable and highly damaging or even fatal deficits for the two major portions of the head and, consequently, by extrapolation, almost certainly can not do so for smaller regions of these two components. This concept has undoubtedly wide acceptance in the scientific community, but its further development is severely hampered by the rigorous adherence, currently for almost two decades, of single specified acceleration or HIC levels, which differ depending on the object under consideration as a requirement for the performance of equipment by government agencies. This official stance permits simple implementation, but is very confusing, as is the failure of these agencies to distinguish between the disparate ideas of head injury "tolerance" and "criteria". It also inhibits the search for a more fundamental approach that would relate mechanical loading to tissure failure.

Two previous attempts have been made to try to define more basic and applicable parameters and their limiting values for specified levels of injury to the head or its components than provided by the HIC (Ommaya, 1983; AAAM. 1987). Although this official criterion was thoroughly castigated, the consensus was that there was currently no better standard that could be readily adopted. Although future modeling improvements were desired, no sequential steps were delineated that might provide such an advance based on sound engineering and biomedical principles.

Furthermore, the present upper bound for linear and/or angular acceleration of one of its functionals as a tolerance criterion has been a source of much dissatisfaction. Clearly, acceleration is not the primary quantity that produces trauma, but rather an excess of local stress, strain or perhaps energy per unit volume for various critical cranial components; their failure values for the most severe injury or a specified percentage of this level for lesser trauma should be determined. In addition, serious questions have been raised concerning validity of the recommended maximum dosage, as these have been derived by substantial manipulation of the data as well as a variety of scaling procedures. Alternatives to the stipulation of an acceleration criterion have been proposed in terms of strains or deflections using simple lumped-mass systems (Stapp Conf., 1971).

Damage-related Criteria

In this sense, a Mean Strain Criterion (MSC) proposed by Stalnaker et al. (1971) and McElhaney et al. (1973) was obtained from the equations for the relative displacement of two masses comprising head regions, separated a by parallel spring and dashpot. The constants for the model were determined from impact tests on primates where loading was correlated with level of injury found upon autopsy, from mechanical impedance data of the primate human cadaver heads, and by employment of dimensionless scaling and extrapolation to permit application of the primate data to human tolerance. Results were expressed in terms of a relation between mean strain (related to average linear acceleration) and AIS for both side and frontal loading, the first attempt to correlate degree of trauma with the direction and magnitude of the blow. The initial model was improved (Stalnaker et al, 1987) by inclusion of an additional dashpot that provided improved accord with head impedance data. The new version was evaluated in four loading directions, and the energy dissipated in this system correlated well with both AIS and HIC values.

A viscous tolerance criterion for soft tissues was proposed by Lau and Viano (1986) that was compared to both the MSC and the HIC by Viano (1988). It is considered particularly useful for soft tissue injury in the trunk. A variant suggested by Viano is the Brain Compliance Model; both are lumped-parameter representations.

Both Stalnaker's and Viano's models are substantial advances over the acceleration criteria in that they permit the evaluation of an average relative displacement of the brain, and hence a mean strain which is a physically far more realistic variable against which to measure damage. Furthermore, Stalnaker's cross-correlation using animal pathology and scaling parameters to humans, and, similarly, with the advent of sufficient experimental data, also that of Viano provide a unique correspondence with injury level and strain magnitude. The portrayal of this information on an acceleration-time diagram is secondary, most likely prompted by the need to conform to the current required standards. However, these procedures still average out the traumatic effects for both the skull and the brain.

Objective of Advanced Criteria

It should be the purpose of model advances to (a) permit an evaluation of the field parameters throughout the head over the critical period of time and determine their peak values for various critical tissues, and (b) using this information, to establish the response of these tissues and ascertain whether this exceeds failure limits based on standard mechanical parameters such as strain, deformation, stress or pressure that either are known or need to be defined for various components. When tissues perform only mechanical operations, the failure condition can be equated to rupture; however, in other cases, where a nervous or control function is involved, the allowable physiological limit must be set at a much lower level. Here, the most promising direction for such a rational effort is a continuation, amplification and expansion of the pioneering work of Thibault (1989) who considers mechanical/chemical interactions due to loading of neurons; unfortunately, space limitations prevent a further discussion of this topic. However, in both cases, the computed stress and strain histories at selected head positions determined from the equations of continuum mechanics, subject to appropriate loading condition on the skull, must be correlated with these limiting values producing physical or neurological failure of specific tissue.

APPROACH TO DEFINE A MORE MEANINGFUL CRITERION

Tissues Affected

The three components or tissues where a sufficient basis is available to commence a mechanical analysis of possible failure under load application are the skull, cerebral blood vessels and an individual axon. The skull can be considered as a sandwich shell with inner and outer layers of compact bone and an osseous honeycomb core. Perrone (1976) suggested an initial approach to examine the possiblility of skull fracture by applying the two-displacement-component thin-shell equations of motion to an axiymmetric spherical cap with various thicknesses ranging from 0.15-0.30 in. This system was loaded over an axisymmetric area by a uniform presure with triangular time dependence. Failure was based on tensile fracture stresses for compact bone (Wood, 1971).

More Accurate Portrayal of the Head Impact Process

The previous relatively simple analytical models can now be replaced by more accurate calculations from a finite element procedure where the skull is represented by a three-dimensional sandwich shell of an elastic-brittle material filled with a viscoelastic fluid. If the skull impact results from contact of another mass of specified geometry at a known velocity, the calculation can proceed by taking into account possible deformations of the striker. If the modulus of the latter is quite high relative to bone, such as would be the case for metal or concrete (but not necessarily for wood), the deformation of the striker can be neglected relative to those of the cranium. A number of calculations of this type involving simple models of head configurations and non-viscous material properties have been published (cf. Shugar, 1975; Khalil and Viano, 1982, 1984); their complexity can be increased at will and the corresponding peak stresses can be compared to the experimental skull fracture stress. If the object is not only to establish whether fracture is produced, but also of what type and the extent of such failure, then appropriate fracture criteria as well as a continual process of rezoning of elements in the failure region must be embedded in the computer program. This procedure has not been rigorously established even for the homogeneous and isotropic substances representing metals, much less for the complex aggregate of the skull; however, the methodology for the pursuit of this topic is available and its execution will require at most acquisition of further material property data.

Critical Failure Condition

The author believes that the greatest promise for the delineation of physically more resonable criteria of brain damage lies in further analytical modeling of tubes under dynamic loading, as such a structure represents both a blood vessel and an axon. Before specifying the precise continuum-mechanical problem whose solution is suggested as a significant step towards specifying rational loading limits, a similar, albeit somewhat simpler situation that has recently been successfully investigated will be presented here. The original motivation for this case was a study of life-support systems; however, this example is provided not only to illustrate the general approach suggested for this modelling process, but also because the result have a direct bearing on and can, in fact, serve as a bound to the actual behavior of cerebral vessels to dynamic loading.

PARADIGM VESSEL INVESTIGATION

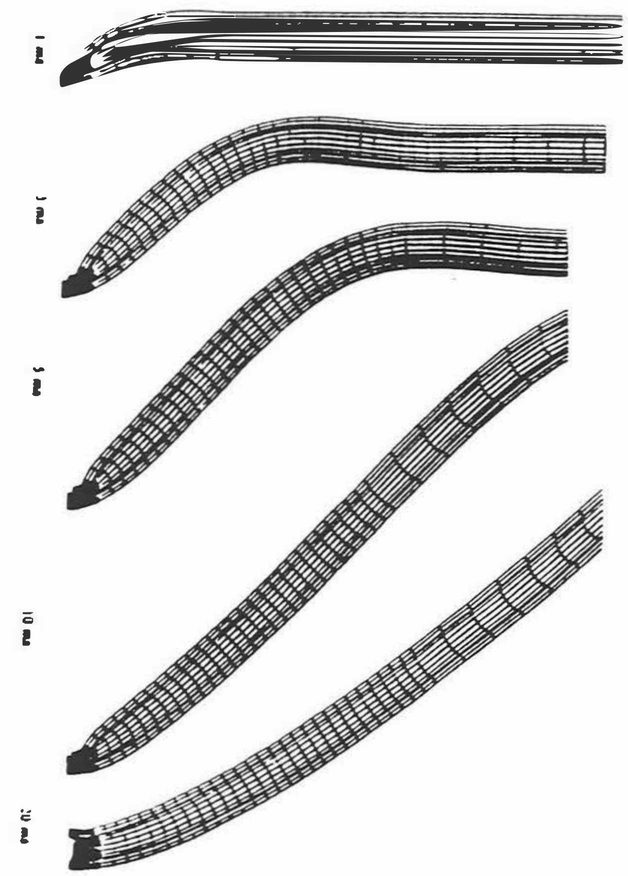
Prototype Problem

The prototype problem consisted of a coordinated experimental, analytical and numerical investigation of the large-deformation response of a long circular visoelastic tube to central transverse impact by a sharp-edged striker (Luo, 1988). This study was performed both for an empty and a water-filled tube of Nalgene, a medical grade ester-plasticized compound of polyvinylchloride with an outer and inner diameter of 7.94 and 4.76 mm and a length of 1.34 m placed in a vertical position and supported at the ends by tension springs. The tube was modelled both elastically and as a standard linear solid so that only the extreme limits of the material constants and the decay time needed to be specified; the structure was represented both as an inextensible string and as a Timoshenko beam, both of infinite extent. This simplification in the boundary condition was valid as the maximum strain and excursions near the impact point occurred before reflected waves return to this position. Since the presence of water provided no contribution to the bending resistance, its effect was included solely by an adjustment of the mass per unit length. The modulus of elasticity was found to vary by 2.5 decades over a frequency range of 10^6, indicating the truly viscous nature of the tube material.

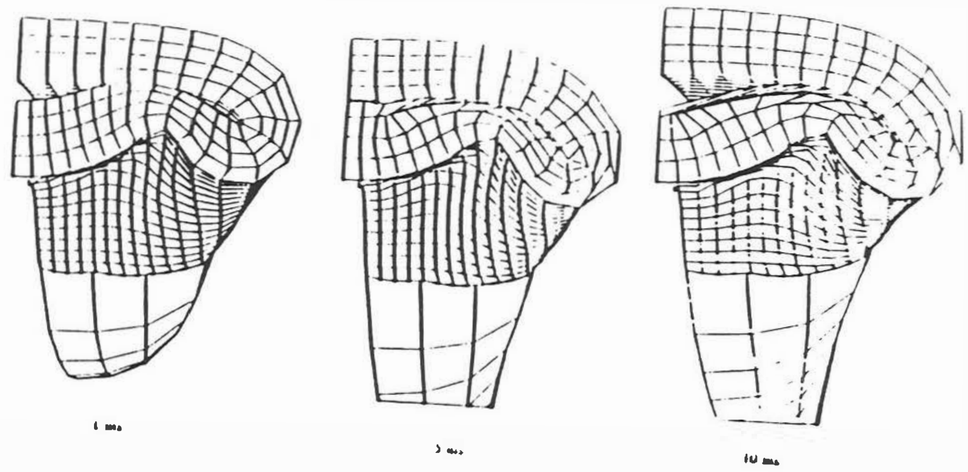
For each of the four structures examined, the analytical solution was obtained by the method of characteristics. Local contact of the striker resulted in a pinching effect which was modeled by a spring, also considered as either elastic or acting as a standard linear solid. Completely numerical solutions were obtained using the code DYNA3D on the San Diego Cray supercomputer. Experimental investigations consisted of the firing of a 50 g aluminum tube containing a force-measuring tranducer at speeds of 11 and 22 m/s against the center of the tube on which reference marks had been painted for displacement and strain measurement. These data were acquired from a framing camera operating at a speed of 1000 pps and from an electro-optical camera, repectively. The pressure of the water, when present, was monitored by gages at two stations, but the data could not be compared to either analytical or numerical results since these accounted only for the mass, but not the pressures in the fluid.

Computed Results

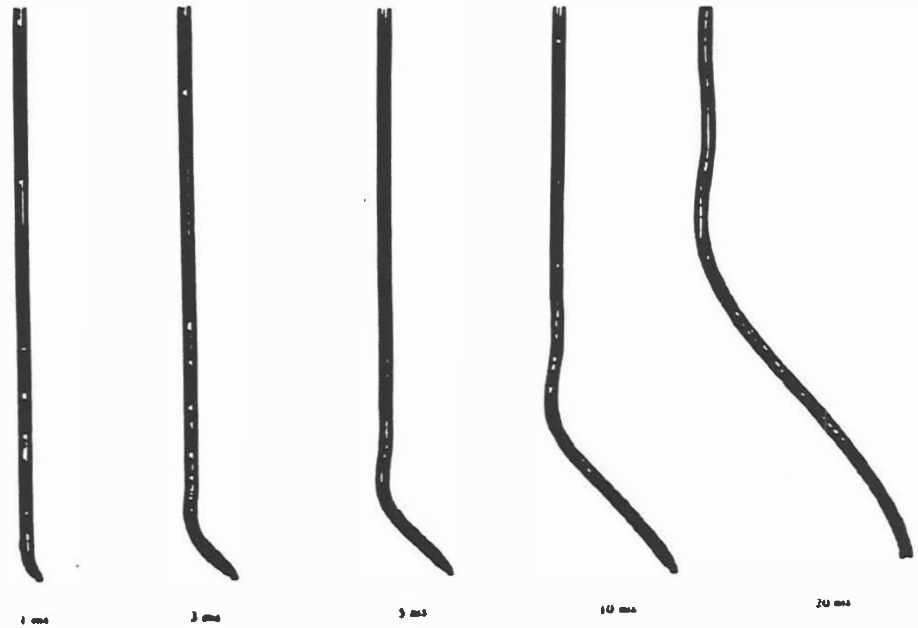
Figure 1 shows the results of the finite element computations for the empty tube at various times after impact at a speed of 22 m/s; part (a) shows the global deflection for half the tube, part (b) that near the impact point, and part (c) depicts the pinching phenomenon, not observed in this form experimentally. Figure 2 provides a comparison of the predicted and observed response for the water-filled tube struck at 22 m/s; part (a) portrays the force history at the impact point, part (b) the deflection histories at several tube stations, both for a preload of 2 lb, and part (c) displays the strain history at a position 430 mm from the impact point for three different preloads. This provides clear documentation that the results of both the phenomenological and numerical analysis are in very good accord with the experimental data, and that, hence, such predictive procedures can be confidently employed to provide a good estimate of the maximum deformation and strain conditions for the specified set of impact conditions. These peak magnitudes can then be compared with a priori specified limits; in the case of Nalgene, for example, the ultimate tensile strain has a value of about 2 occurring with a corresponding uniaxial stress of 6.2 MPa (Dual, 1984).



(b)

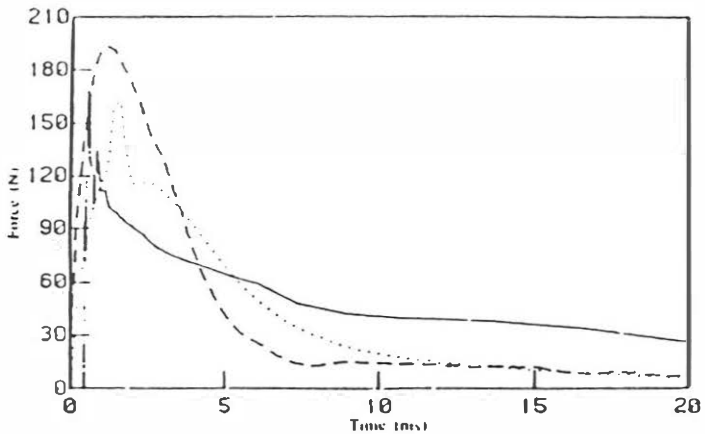


(c)

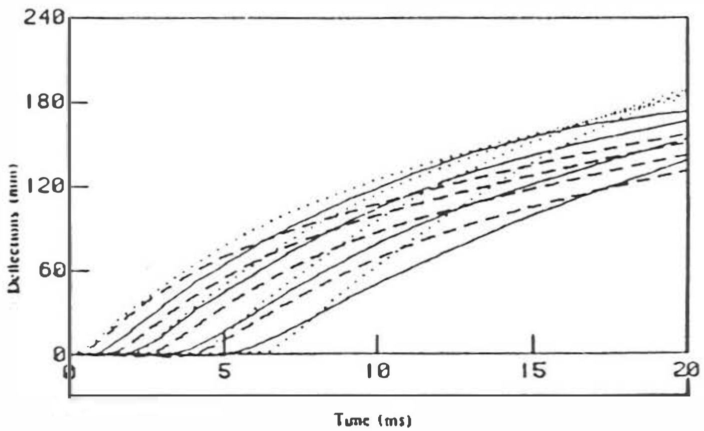


(a)

Fig. 1 Finite Element Results for the Transverse Impact on an Empty Nalgene Tube by a 50 g mass at a speed of 22 m/s for various times after impact

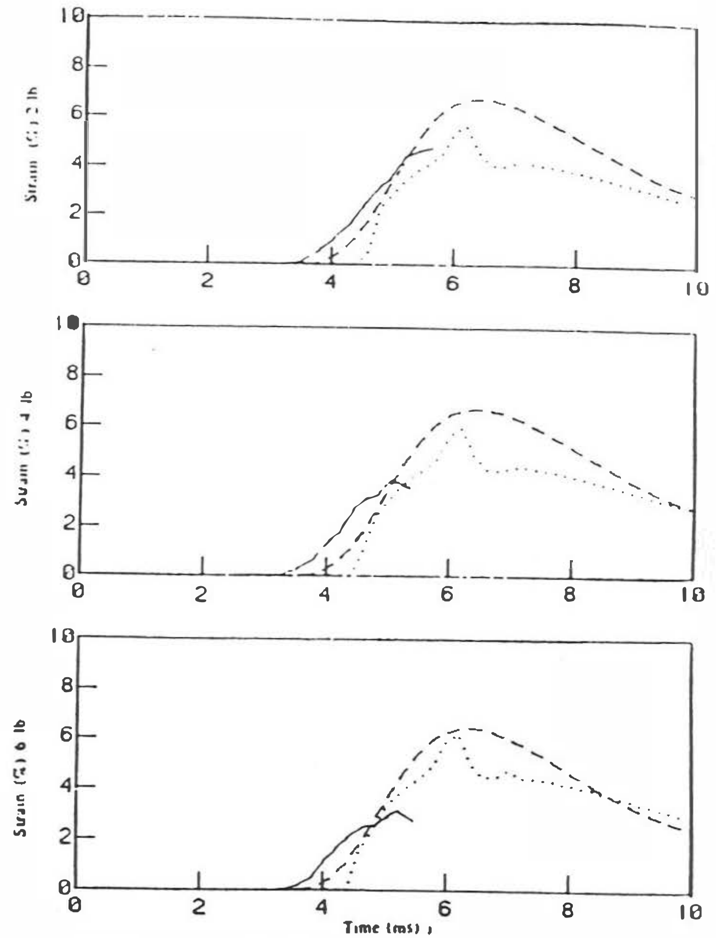


(a) Impact force history at the impact point



(b) Deflections at 0, 40, 80, 120 mm from the impact point (from top to bottom)

Dash: Viscoelastic Beam Dot: Elastic String Solid: Experimental Data.



Dash: Viscoelastic Beam Dot: Elastic String Solid: Experimental Data by Optfollow

(c) Strain history at a position 430 mm from the impact point

Fig. 2 Comparison of Analytically Predicted Response for Tube Models represented by an Elastic String and a Viscoelastic Beam, respectively, for the Water-filled Nalgene Tube Struck by a 50 g Hollow Aluminum Cylinder at a Velocity of 22 m/s and Corresponding Experimental Data

CEREBRAL VASCULAR RESPONSE ANALYSIS TO DYNAMIC LOADING

System Characteristics and Load Histories

The following strategy is suggested for the study of local vascular failure in the brain resulting from a nonpenetrating blow to the head. The first step is the determination of the history of stress or pressures, deformations and/or strains and loading and/or deformation rates at all critical points within the cranium due to the application of a specified impact. This can be evaluated as an impact problem (Goldsmith, 1960) involving two bodies of given mass and geometry striking each other at a specified initial velocity. The material and structural characteristics as well as the speed characterize local contact phenomena, such as skull fracture and/or indentation, based on a stress or strain criterion, as well as the propagation of waves throughout the cranium with due account for reflections at boundaries and the potential for fluid communication through the foramen magnum. In this part of the analysis, the contents of the brain can be depicted with sufficient accuracy as a homogeneous fluid of appropriate density and viscoelastic characteristics. Several typical situations can be analyzed, such as, for example, the contact of a helmeted (or unhelmeted) head of a motorcyle rider with the pavement or of a car driver with a windshield at several representative velocities, or comparable situations involving industrial or sporting accidents or situations from everyday life, such as slip-fall or bumping situations.

Vessel Response

After such loading histories in one or more critical regions have been established, it is suggested that this serve as the boundary condition for the examination of the response of a viscoelastic tube with dimensions corresponding to a typical cerebral vessel which is surrounded by a viscoelastic liquid with the properties of cerebrospinal fluid and carries within it a non-Newtonian liquid, blood. It is not necessary to include blood flow per se, as it has been demonstrated that flow speeds are three orders of magnitude or more less that wave velocities, and that, except in cases of obstruction or bifurcation, an analysis considering only a stationary liquid provides an adequate description of the events under dynamic loading (Barez et al., 1979).

Mechanical Properties and Failure States

The constitutive equation for blood has been described by Fung (1981) and Caro (1978) as a Newtonian fluid whose description relating stress to hydrostatic pressure and strain rate is not overly complicated. The behavior of blood vessels has been portrayed in terms of quasi-linear viscoelastic behavior based on a pseudoelastic concept (Fung, 1981). Detailed studies of uniaxial tensile test results of cerebral vessels (Chalupnik et al.,1971) indicate a behavior pattern similar to arterial tubes; some typical values of the constants for certain autopsy specimens are also indicated. In these experiments, loading was limited to 3.5 MPa; breaking strength was estimated at 7-14 MPa (Daly, 1986), a value considerably greater than the maximum values of 1.5 MPa reported by Yamada (1970) for arterial vessels who also cited expansion strength under internal pressure to be less than 1/15 of this value. Yamada also cites values of 100 percent or more for the ultimate tensile strain. Clearly, further investigations are needed to provide more reliable information concerning the permissible loads on these tissues. It is suggested that in addition to uni-axial ultimate tensile strain, the corresponding ultimate extension (Stacey, 1981) and shear strains should be considered as most appropriately representing a failure criterion.

Geometric Considerations

Initially, vessels can be approximated as uniform, straight and fixed at the ends. Subsequent refinements should include variations in both diameter and wall thickness, as well as consideration of bifurcations. By building upon the knowledge gained from and analysis of the simplest structure that can be reasonably regarded as representing a zero-order model of the vessel to be analyzed, complexities can be added step by step so as to eventually permit predictions for the behavior of the actual vessel under similar loading. It should be emphasized that this loading is both time-dependent and distributed over the length of a vessel. After extensive categorization of the most traumatic local conditions conceming blood vessel rupture, it should then be possible to define the maximum extemal loading effects that will prevent such catastrophic regional failure. A parallel approach can be applied to the dysfunciton of axons and neurons with due consideration for chemical processes produced by mechanical action.

CLOSURE

It is suggested that the current global acceleration criteria/standards for closed head injury be replaced by a two-tier system of load limits based upon skull fracture determined from contact analysis of an elastic/brittle sandwich shell and cranial trauma based, in first line, on rupture characteristics of blood vessels. The potential for the failure of the latter should first be ascertained by determining the temporal and spatial distribution of the field variables in a viscoelastic fluid continuum enclosed by the skull, with provisions for fluid communication through the foramen magnum and location of the most significant pulse levels. Such histories should be used as the boundary condition for blood-filled vessels suspended in a viscoelastic fluid and attached at the ends to determine their strain response and to find the relation of such values to known failure limits. The structural model of the vessels should be successively increased in complexity. By consolidating the information obtained in this fashion, and subsequently complemented by parallel studies on axons and neurons, a more rational head injury criterion based on local failure rather than global acceration should evolve.

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