INTRACRANIAL PRESSURE TRANSIENTS CAUSED BY HEAD IMPACTS

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ABSTRACT

It has been hypothesised that short duration negative pressure pulses in the brain, caused by blunt impacts, can reach sufficient magnitude to cause cavitation in blood vessels and could explain the appearance of contusions, observed in many cases, at the pole opposite to impact (contre-coup injury). A finite element model of pressure wave propagation in the brain was developed in order to numerically explore the peak pressures arising from an applied force time history. The sensitivity of the pressure response in the brain to changes in material and geometrical properties of the skull and brain as well as to changes in the applied force time history was extensively explored using the model.

CAVITATION has long been postulated as a possible brain injury mechanism during head impacts. However it is still unclear whether negative pressures occurring in the brain due to transient linear acceleration can reach sufficiently high magnitudes to cause cavitation. Anzelius (1943) was one of the first to study analytically the response of the head to an axisymmetric impact with a model which consisted of a rigid spherical shell filled with an inviscid fluid. Engin (1968) proposed a fluid filled elastic shell analytical model and studied the response to normal delta-function loading and Kenner and Goldsmith (1972) extended the analysis to loadings of finite duration. More recently, the finite element method has become the numerical approach of choice, principally because of the ease with which irregular geometry and material non-linearities can be modelled.

In the present study the head is modelled as a fluid filled spherical shell using a finite element approach. This head model is then used in a number of parametric studies to explore the sensitivity of the pressure response in the brain to changes in material and geometrical parameters. The numerical model presented in this paper is admittedly simplistic: the head is modelled as a perfect sphere, the skull is assumed homogeneous and of uniform thickness, the bone material model used is linearly elastic, and the brain is assumed to be an inviscid homogeneous fluid. Not only are these gross simplifications, but the reader may rightly wonder why a more complex model was not developed since there are, a priori, no reasons not to include more realistic geometric features and more complex material models in a finite element model as has been done by a number of authors (for a review of finite element models of head impacts, the reader is referred to Voo et al (1996) and Sauren and Claessens (1993)). Whilst the more realistic finite element head models in the open literature have provided many insights into the response of the head to impact, their very complexity and the large variability in geometric and material properties between the finite element models proposed by different authors has made it difficult to identify critical parameters/features of the skull and brain which significantly influence the response. By reducing the complexity of the problem, (and the number of variables), the authors were able to more clearly identify regions of significant dynamic magnification of the intracranial pressure. In particular, the collapse on scaled impact duration in the present study shows the effect of impact duration on the pressure response in a more general way than previous work and the large dynamic magnification associated with shell flexibility at short scaled durations is also clearly highlighted.

MODEL DESCRIPTION

INTRACRANIAL PRESSURE MODEL: The shell was assumed to be spherical, homogeneous and of constant thickness and to have linear elastic material properties. The fluid filled the shell completely and was assumed to be inviscid and to behave linearly. A sketch of the fluid filled shell is given in Figure 1.

The base line geometrical and material properties of the shell and fluid were the same as the values taken by Engin (1968), given here converted into SI units, and are denoted with an o subscript: fluid density $\rho_{o\text{-}f}$ = 1002 kg/m^3 (f subscript denotes fluid) and bulk modulus $B_o = 2.18\times10^9$ Pa (values for water used to approximate brain material); Young's modulus of the shell (skull) E_o = 13.79×10^9 Pa, density $\rho_{o\text{-}s}$ = 2140 kg/m^3 (s subscript denotes shell) and Poisson's ratio ν_o = 0.25. The inner radius of the shell was taken as a_o = 0.0762 m and the shell thickness was taken to be h_o = 0.00381 m. The baseline finite element model had a total mass (shell + fluid) of m_o = 2.45 kg.

The time-history of the applied force was a standard shape with finite first and second derivatives (Hanning squared function) applied as a uniform pressure distribution over a sector of the outer shell surface. The base-line impact was modelled as a uniform pressure acting radially and symmetrically on a spherical cap of sector half angle φ = 15° with a Hanning squared pressure-time history given by $P(t) = F(t)/[\pi\, a^2 \sin^2\varphi]$ where $F(t) = F_o$[1/2 - 1/2cos

$(2 \pi t / T_p)]^2$, t is the time, $T_p = 1$ ms is the duration of the applied load, and $F_0 =$ 10 kN is the maximum force in the x direction.

In the following numerical studies, unless explicitly stated, the values of all parameters are as given above.

FINITE ELEMENT REPRESENTATION: The symmetry of the model was exploited to reduce computational cost but a three dimensional representation was kept in order to be able to readily extend the analysis to non axi-symmetric problems. The basic model used to compute the results was a 30° wedge one element thick as shown in Figure 2 with 24 shell elements for the outer shell and 384 eight noded linear brick elements used to model the fluid. Displacement of the nodes along the 'cut-out' planes was restrained out-of-plane. In order to model an inviscid fluid the shell-fluid interface was modelled as a sliding contact surface; that is a zero penetration/separation boundary condition was enforced at this interface but fluid elements were not restrained from slipping along the shell surface.

The numerical convergence of the results obtained using the basic finite element model described above was verified by running the analysis with a more refined model having double the mesh density in both the x and y coordinates and of half the wedge 'thickness' (15°) (see Figure 3). The pressure response in the fluid at the pole and antipole was computed using this finer meshed model as well as the coarser meshed model for a wide, but by no means exhaustive, range of parameters and reasonable agreement between the numerically predicted responses was achieved. Although the finer mesh would provide more accurate results, it is also correspondingly more cpu intensive, and hence the coarser mesh was used for the sensitivity studies.

It should be noted that in the computations the actual maximum applied pressure was several orders of magnitude less than that required for $F_{max} = 10$ kN to ensure that the observed response was in the linear range. The pressure results plotted were then simply scaled up appropriately from the computed values. This scaling up procedure is obviously not entirely legitimate and the pressure response results computed in the linear range could have been presented non-dimensionalised on the maximum applied pressure (or the pressure response for the quasi-static case). However the results were presented scaled up for a 10 kN maximum force in order to give the reader a better feel for the magnitude of the transient pressures one might expect for an impact force equivalent to approximately 400G whole head acceleration. The reader should therefore be aware that the response will be different for cases in which the applied force-time history causes large deformation of the head (cases for which the effects of geometric non-linearities become significant).

PARAMETRIC STUDIES

We wish to gain a better understanding of the influence on the response of the system of changes in a number of parameters for which either precise values are not known (e.g. material properties of brain and skull) or for which a large degree of variability exists (e.g. skull thickness, impact duration). Accordingly, the sensitivity of the pressure response of the fluid filled spherical shell model to changes in material and geometrical properties as well as to the applied force-time history was explored. Parametric studies of the pressure response in the fluid, at the pole (under the site of impact) and at the antipole (180° opposite to impact site), were performed for changes in the following parameters about the baseline values: Young's modulus, density and Poisson ratio of the shell (skull), bulk modulus of the fluid (brain), and impact duration.

IMPACT DURATION: In Figures 4 and 5, the pressure responses at the pole and antipole for the baseline model but for impact durations ranging from 10 ms to 0.1 ms are plotted against time. For long impact durations (see T_p = 10 ms in Figure 5) the pressure response in the fluid tends towards the analytical quasi-static solution given by $P_\infty = a_o \rho_{o\text{-}f} F(t)/m_o$ as would be expected (quasi-static predicted response for 10 ms impact duration also plotted in Figure 5 for comparison). For the quasi-static case the pressure at the pole rises with the applied force and is mirrored by a decrease in the pressure at the antipole. For the force time history applied in this case the response is a Hanning squared pressure time history rising to a maximum of $a_o \rho_F F_o/m_o$=3.12 bars at the pole and -3.12 bars at the antipole. However, as the impact duration becomes shorter the pressure response starts to deviate from the quasi-static solution. For $T_p \leq 1$ ms the pressure response is both quantitatively and qualitatively different from the quasi-static case with maximum pressures in the fluid increasing dramatically and very high negative pressures occurring not only at the antipole but also at the pole.

YOUNG'S MODULUS OF THE SKULL: In Figures 6, 7, 8 and 9 the pressure at the pole and antipole are again plotted but this time for Young's modulus ratio of the skull $E_r = E/E_o$ ranging from 1/100 ($E = 13.791\times10^7$ Pa) to 100 ($E = 13.791\times10^{11}$ Pa). Also plotted is the analytical quasi-static solution. Analogous results to those obtained for decreasing impact durations are obtained for increasing skull flexibility. For very high Young's modulus (13.791×10^{11} Pa) the pressure response at both poles is virtually indistinguishable from the quasi-static solution (see Figures 6 and 8) but as the assumed Young's modulus of the skull is decreased the shape of the pressure response changes and the peak maximum pressure values observed increase by an order of magnitude.

THICKNESS AND DENSITY OF SKULL: Analogous metamorphoses of the response curves were observed by independently varying the thickness of the shell (skull) h, and the material density of the shell (skull) ρ_S about the baseline values. With decreasing thickness ratio of skull $h_r = h/h_o$ and with increasing skull density ratio $\rho_{S\text{-}r} = \rho_S/\rho_{S\text{-}o}$ the pressure response in the fluid deviates from the quasi-static prediction. For the sake of brevity figures for these two cases are not given here.

POISSON'S RATIO OF SKULL AND BULK MODULUS OF BRAIN: Varying the Poisson's ratio of the shell (skull) from 0 to 0.499 had only a relatively small effect on the pressure response in the fluid (see Figures 10 and 11). Similarly the observed pressure response is insensitive to changes in the assumed bulk modulus of the fluid over a wide range of values about the baseline (water) bulk modulus (see Figures 12 and 13) which seems to suggest that the fluid behaves essentially incompressibly over a large range of values about the baseline parameters chosen. The implications of this are that if we assume the brain to have a bulk modulus close to water (in fact within an order of magnitude of the bulk modulus of water), the flexibility of the skull is far more important than the compressibility of the brain (at least for the simplified model presented here).

COLLAPSING RESULTS OBTAINED FROM SENSITIVITY STUDIES: Values of both peak positive and negative intracranial pressure at the pole and antipole over a wide range of parameter values are collapsed by normalising the impact duration on the period of oscillation T_Ω of the lowest ovalling mode of the fluid-filled shell. The period of oscillation T_Ω was calculated by the authors based on the modification of an exact analytical solution for a multi-layered solid sphere (Jiang et al.,1996).

The peak (maximum) negative and positive pressures observed at the pole and antipole respectively are plotted in Figures 14 and 15 against the log of the non-dimensional ratio of T_p/T_Ω. The ratio T_p/T_Ω was varied by changing (i) the impact duration T_p, (ii) the Young's modulus (E), (iii) the thickness (h), and (iv) the density of the skull (ρ_S) independently over a wide range about their baseline (Engin) values. Excellent agreement between the results can be seen in the peak pressures obtained at the pole (Figure 14), and good agreement at the antipole (Figure 15). This clearly shows that the ratio of the impact duration to the period of oscillation (ovalling mode) T_p/T_Ω is a very good predictor of the response of the system. As this ratio becomes large (that is as $T_p >> T_\Omega$) the response tends towards the quasi-static solution. However as T_p approaches T_Ω, the pressure response observed deviates dramatically from the quasi-static case with one order of magnitude increases in the maximum pressures observed. The response not only deviates quantitatively from the quasi-static solution but also qualitatively with very high positive and negative maximum pressures observed at both the pole and antipole.

DISCUSSION:

A number of interesting results have been obtained from the parametric studies on the simple numerical model presented in this paper:

- The pressure response in the fluid is insensitive to changes in the assumed bulk modulus of the brain over a very wide range of values: 2.18×10^8 Pa $< B_o < 2.18\times10^{10}$ Pa.

- Very high transient pressures are observed at the pole and the antipole as the impact duration becomes shorter and/or as the skull stiffness is decreased (either by decreasing the skull thickness or decreasing the assumed Young's modulus of the skull). Interestingly, large transient negative pressures are observed not only at the antipole but also at the coup site, suggesting cavitation could also be an injury mechanism under the site of impact.
- Results obtained in the parametric studies can be collapsed by normalising the impact duration on the period of oscillation T_{Ω} of the lowest ovalling mode of the fluid-filled shell. For small values of normalised impact durations, typically corresponding to 0.5 ms or less on an adult head, negative pressures of order 40-60 bars are predicted under the impact site for a 10 kN peak applied force, and negative pressures of order 20-30 bars are predicted at the opposite pole. Knowledge of *in-vivo* cavitation thresholds is not sufficient to say whether cavitation would occur under these conditions; however it remains a strong possibility.

Whether these results remain valid when additional complexities are introduced into the model, such as non-linear material properties and more realistic cranial geometry, remains to be explored.

ACKNOWLEDGEMENTS:

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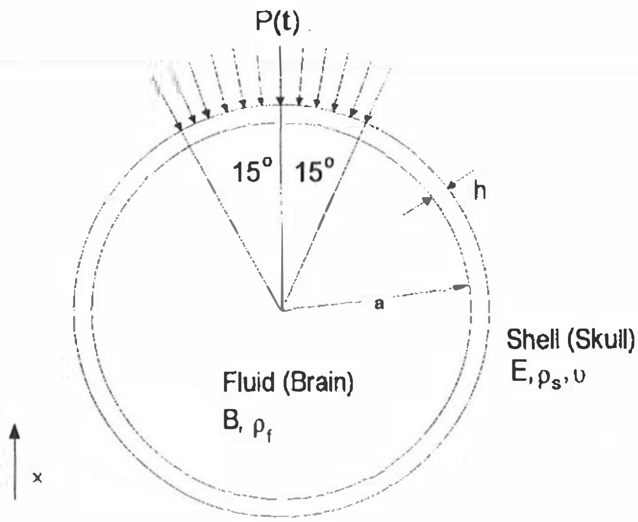

Figure 1: Sketch of fluid-filled spherical shell

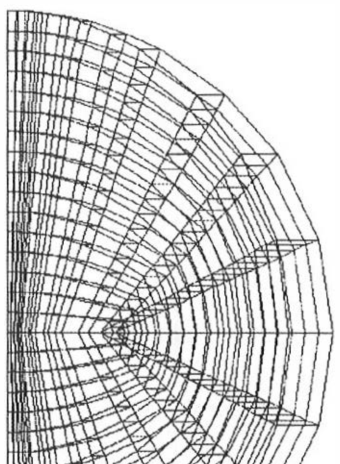

Figure 2: Low density mesh
(384 fluid elements)
(24 shell elements)

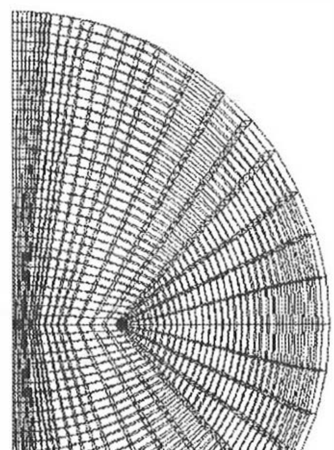

Figure 3: High density mesh
(1536 fluid elements)
(48 shell elements)

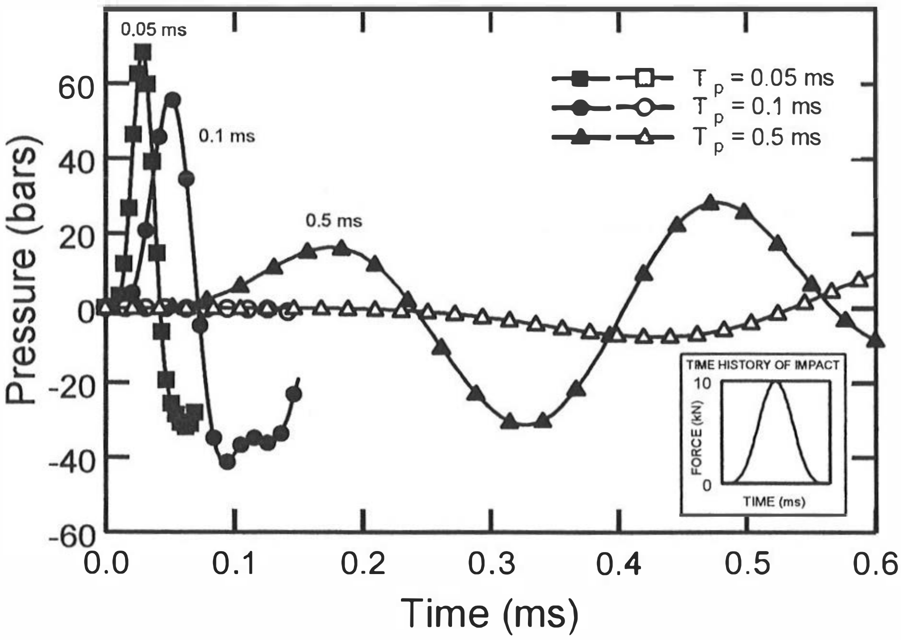

Figure 4: Pressure response in fluid at pole and antipole for T_p = 0.05, 0.1 and 0.5 ms.

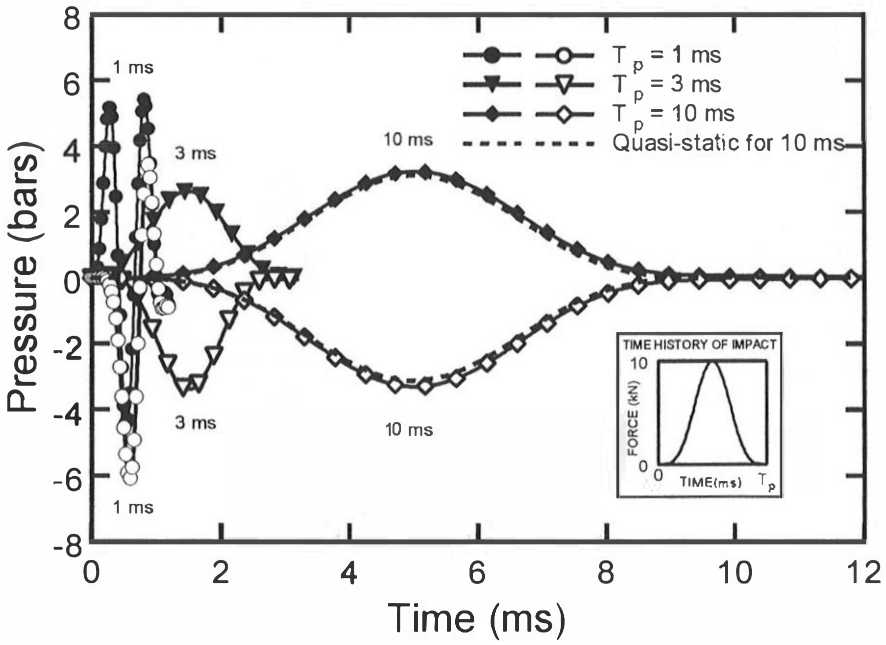

Figure 5: Pressure response in fluid at pole and antipole for T_p = 1,3 and 10 ms.

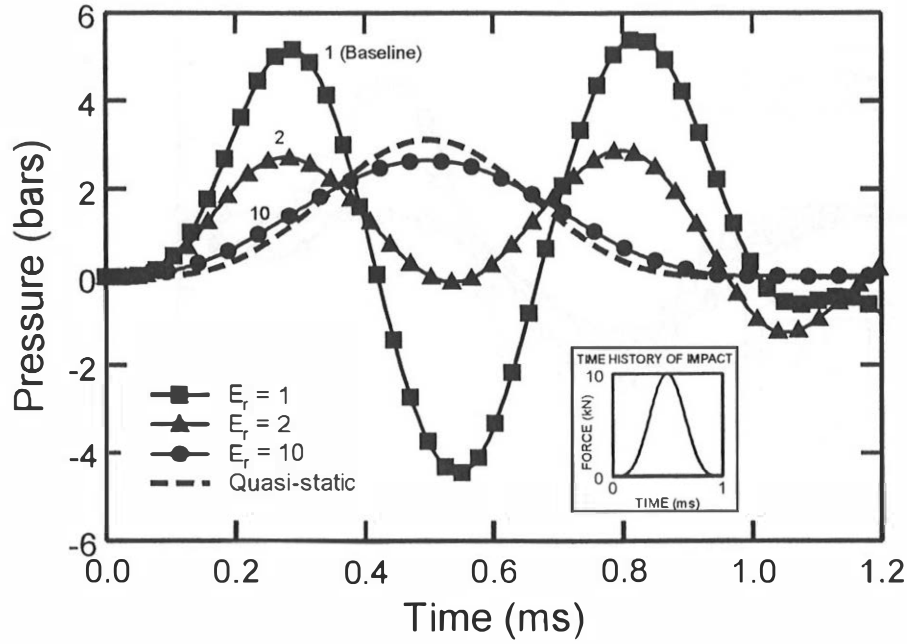

Figure 6: Pressure response in fluid at pole for $E_r = E/E_o$ ranging from 1 to 10.

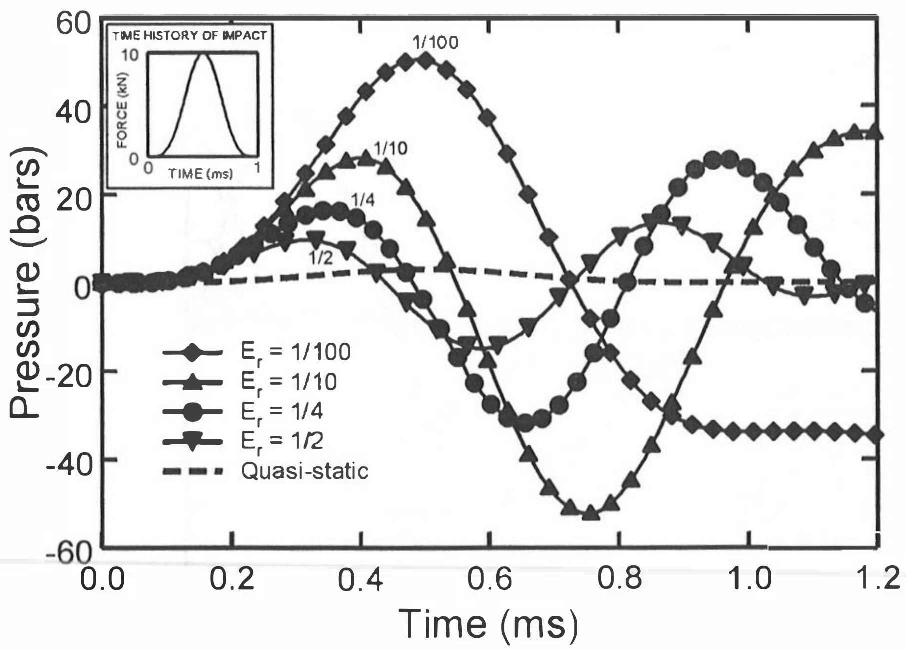

Figure 7: Pressure response in fluid at pole for $E_r = E/E_o$ ranging from 1 to 1/100

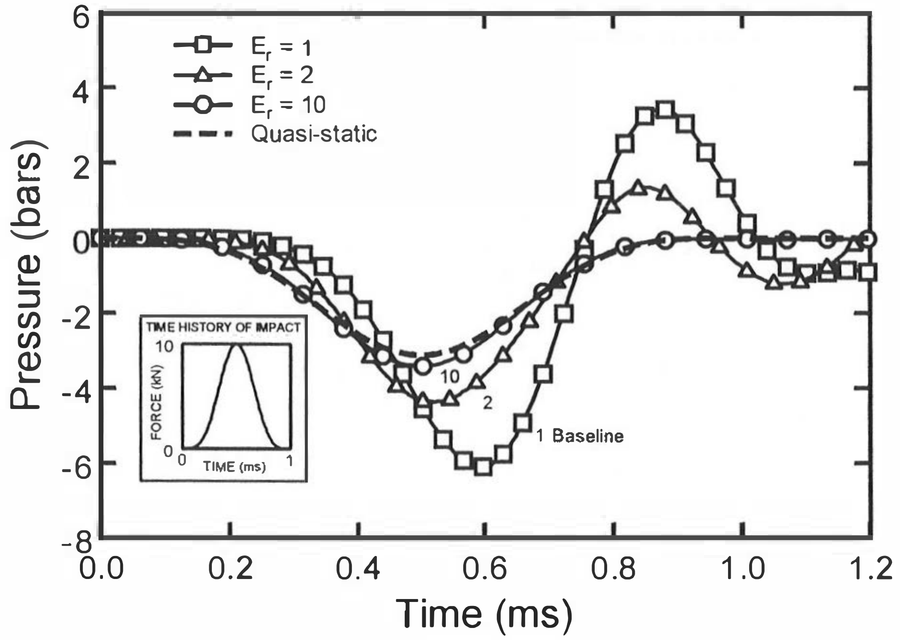

Figure 8: Pressure response in fluid at antipole for $E_r = E/E_o$ ranging from 1 to 10.

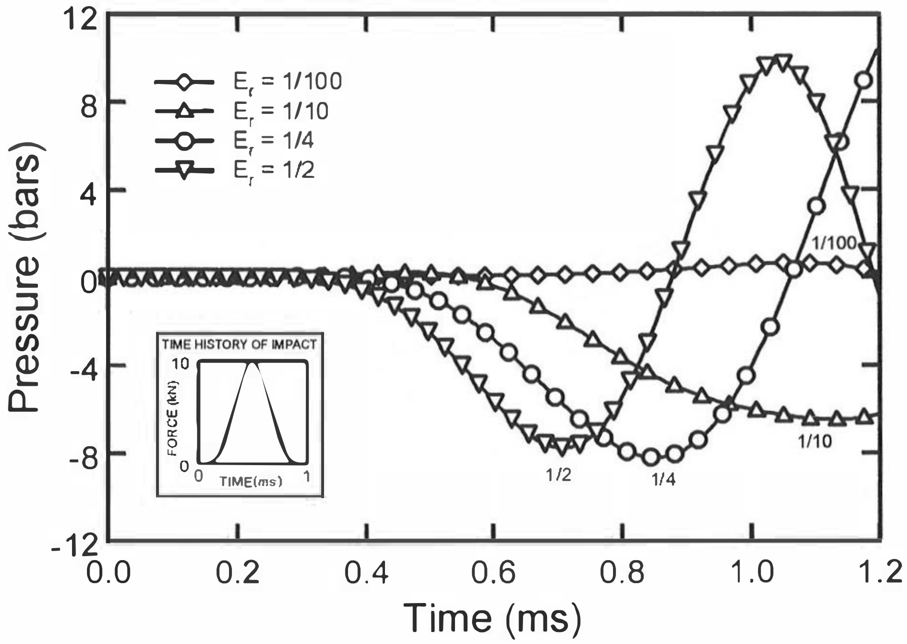

Figure 9: Pressure response in fluid at antipole for $E_r = E/E_o$ ranging from 1 to 1/100.

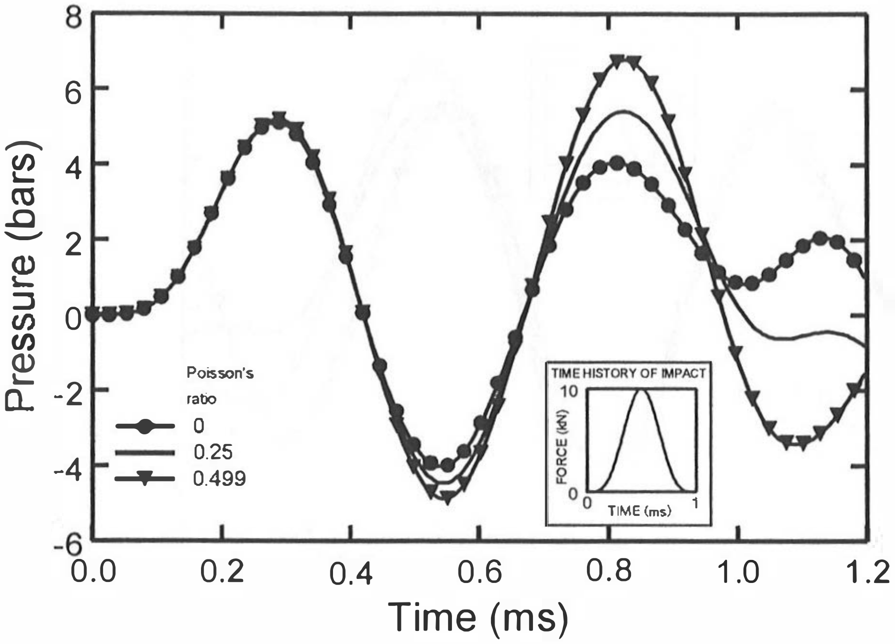

Figure 10: Pressure response in fluid at pole ν_s = 0, 0.25 and 0.499.

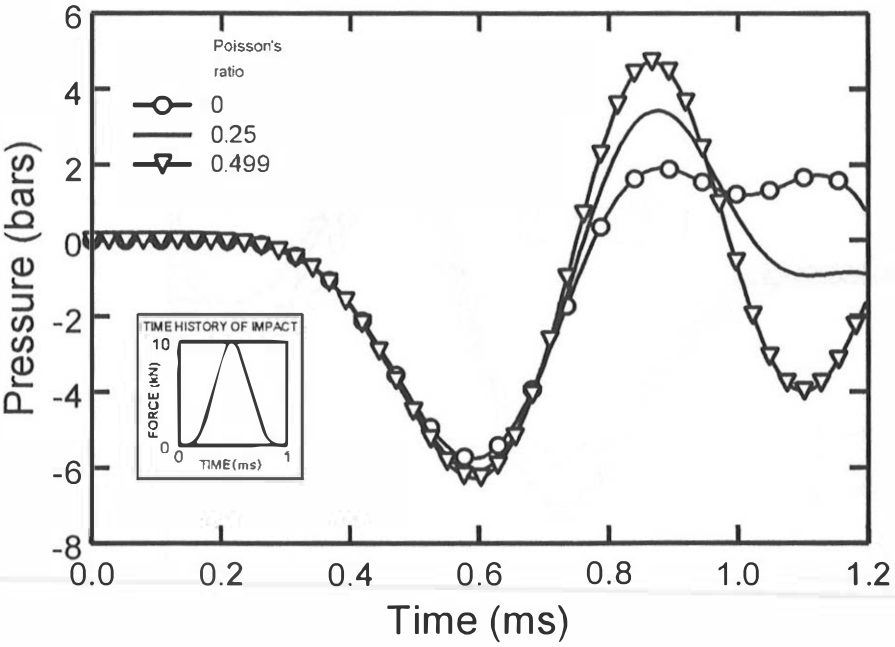

Figure 11: Pressure response in fluid at antipole ν_s = 0, 0.25 and 0.499.

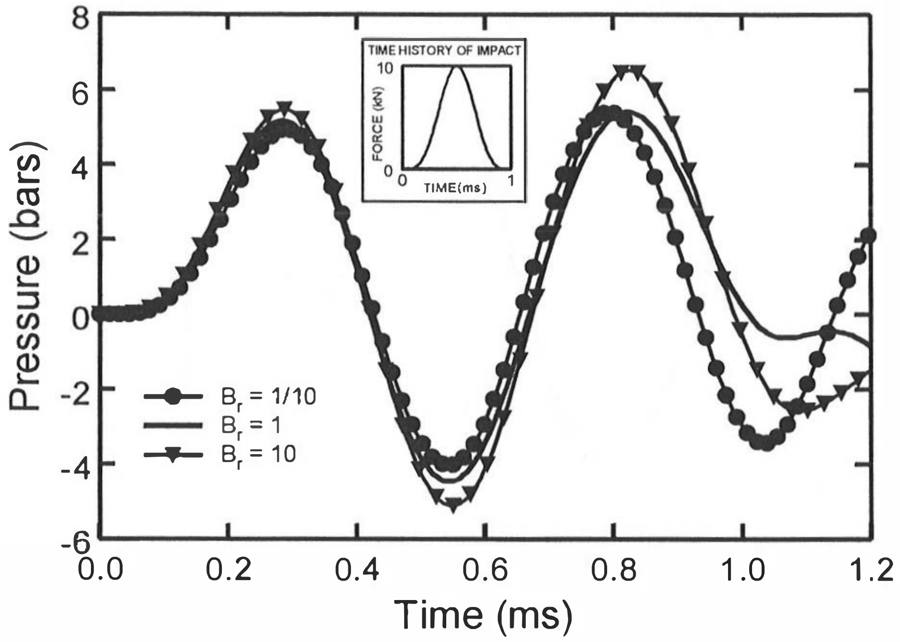

Figure 12: Pressure response in fluid at pole for $B_r = B/B_o$= 1/10, 1 and 10.

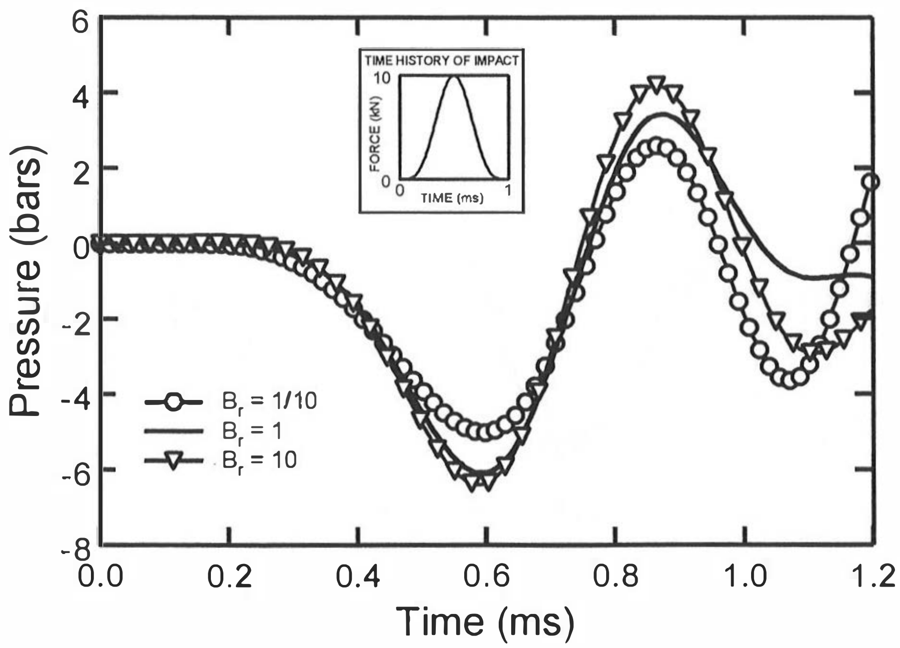

Figure 13: Pressure response in fluid at antipole for $B_r = B/B_o$= 1/10, 1 and 10

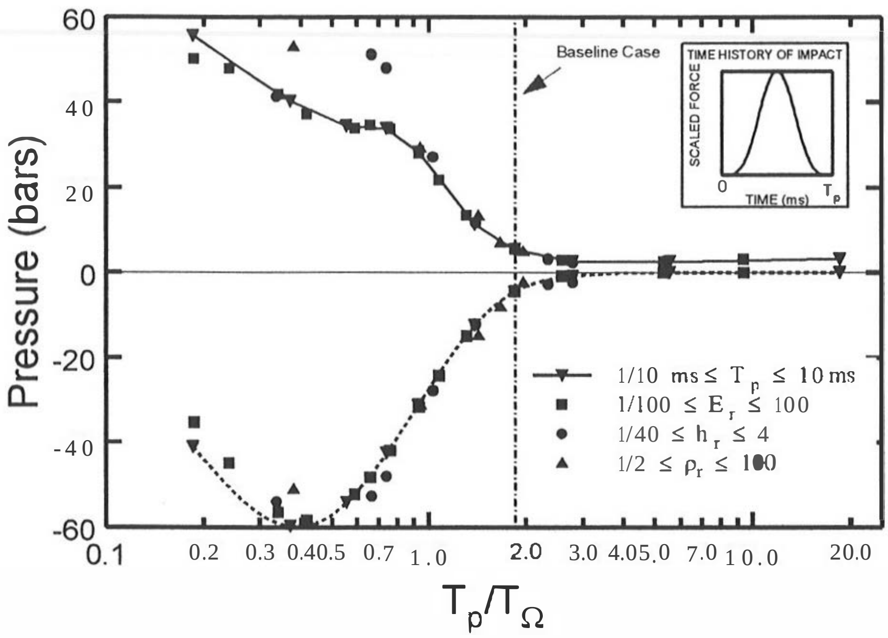

Figure 14: Peak pressure response in fluid at pole for (from left to right):
T_p =0.1,0.2,0.3,0.4,0.5,0.75,1,1.5,3 and10 ms
E_r=E/E_o=1/100,1/60,1/30,1/20,1/10,1/8,1/6,1/4,1/3,1/2,1,2,10,100
h_r=h/h_o=1/40,1/10,1/8,1/4,1/2,2,4
ρ_r=ρ/ρ_o =100,10,4,2,1/2

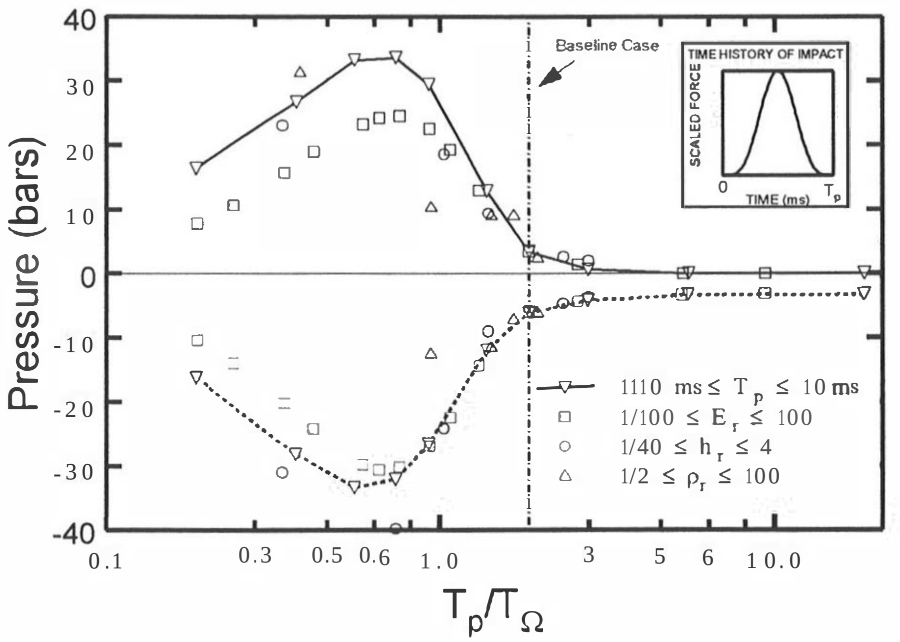

Figure 15: Peak pressure response in fluid at antipole for (from left to right)
T_p=0.1,0.2,0.3,0.4,0.5,0.75,1,1.5,3 and 10 ms
E_r=E/E_o=1/100,1/60,1/30,1/20,1/10,1/8,1/6,1/4,1/3,1/2,1,2,10,100
h_r=h/h_o=1/40,1/10,1/8,1/4,1/2,2,4
ρ_r=ρ/ρ_o=100,10,4,2,1/2