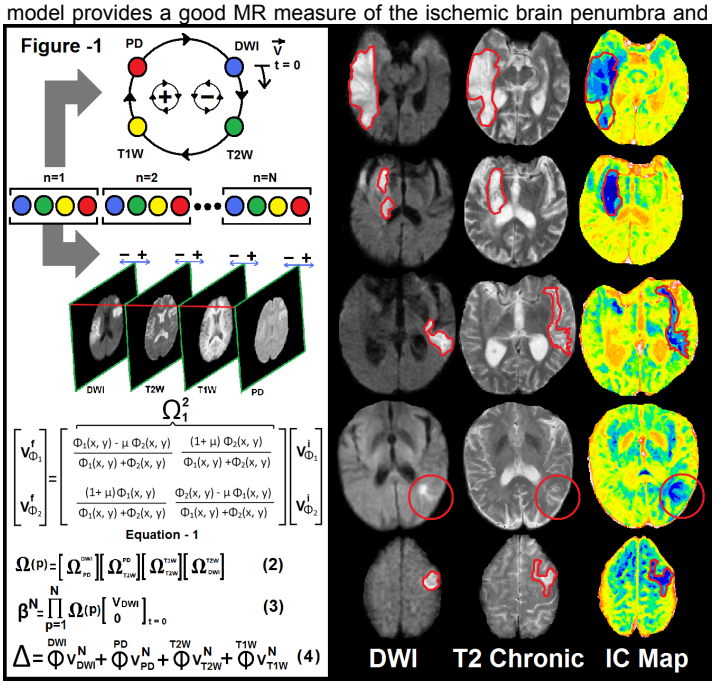
MRI Measurement of Ischemic Brain Penumbra Using an Inelastic Collision Model

H. Bagher-Ebadian[1,2], P. D. Mitsias[1], M. H. Asgari[1], M. Chopp[1,2], and J. R. Ewing[1,2]
[1]Department of Neurology, Henry Ford Hospital, Detroit, Michigan, United States, [2]Department of Physics, Oakland University, Rochester, Michigan, United States

Introduction:
Multi-parametric MRI analysis of the ischemic lesions of stroke patients demonstrates inhomogeneities in the degree of ischemic injury and recovery potential [1]. Experimental and clinical studies indicate that the likelihood for progression to infarction in the penumbra of physiologically impaired but potentially salvageable tissue surrounding the central core of focal cerebral ischemia is an important factor in evaluating treatment efficacy [2]. Thus, a multi-parametric analysis that increases the ability of investigators to detect and characterize ischemic penumbra in the early stages of stroke may have a profound clinical significance. In this study, a mechanical model of inelastic collision (IC) is recruited and adapted to information theory in order to construct a model-based algorithm for multi-parametric analysis. This study proposes an algebraic model to extract intrinsic characteristic of the tissue using inelastic collapse between different image modalities in which the collision sequence is periodic. The IC model provides an unsupervised algorithm for combining the information from different basis sets to generate a multi-parametric map. The proposed model is applied to MR information obtained from twelve stroke patients. Results imply that the proposed inelastic collision model is capable of characterizing the viability of cerebral tissue using MR information obtained during the acute stage of stroke and that this model provides a good MR measure of the ischemic brain penumbra and the pattern of tissue viability at the chronic stage of stroke.

Theory: An inelastic collision is a collision in which kinetic energy is not conserved. In this model, it is assumed that each image modality at the acute time point is constructed from a set of particles (voxel locations, (x,y)) with different masses (image intensities- Φ(x,y)) arranged in a two dimensional space. Given a periodic sequence *[n=1,2,.., N]* of collision of acute image modalities, this model is used to combine MR acute information to form a multi-parametric map. In the presence of an arbitrary restitution coefficient (μ<1), a unit velocity is assigned to all particles in one of the modalities in the first sequence of collision. Then, all the modalities are brought into collision with each other in form of the repetitive ICs, until a steady state condition is achieved for negative and positive particle flows (See Figure-1). The characteristic matrix (Ω) of each collision, defines the chance and level of information passed, excluded, or combined between the two collided modalities (See Eq. 1). Thus, for *N* cycle of collisions, a chain matrix (B^N) generates velocity information of the positive or negative flow at the end of the cycle (See Eq.2 and Eq.3). Since momentum is conserved in IC model, in the steady state (no more collisions), summation of the momentum map (Δ), for all particles in all modalities is calculated from their final velocity matrices and is used as the multi-parametric map to characterizie the ischemic penumbra and degree of tissue viability (Eq. 4).



Materials and Methods: Twelve patients presenting with acute neurological deficit consistent with stroke, with MRI studies within 24h of onset, were selected. The severity of the neurological deficit was assessed using the National Institutes of Health Stroke Scale (NIHSS) score at the time of each MRI study. MRI studies were performed at the acute time point (<24 h after stroke onset), and outcome time point (90 days after stroke). Patients were excluded if they had cerebral hemorrhage at the acute time point or a history of prior stroke. MRI studies were acquired on a 1.5-tesla GE Signa MR scanner with echo-planar capability (GE, Milwaukee, Wisc., USA). Each MRI study consisted of axial multi-spin echo T_2-weighted imaging (T2WI), T_1-weighted imaging (T1WI) and diffusion-weighted imaging (DWI) with slice thickness of 6 mm. The field of view (FOV) was 240 × 240 mm. For T1 and T2 imaging, the matrix was 256 × 192 and for DWI 128 × 128. Additional parameters for each study were: (a) T1WI: TR/TE = 600/14 ms; (b) T2WI: TR/TE = 2,800/30, 60, 90, 120 ms; (c) axial DWI was performed using an echo-planar sequence, TR/TE = 10,000/101 ms, b-values = 1,000 s/mm^2, 1 NEX. For each patient, four co-registered images (T_1, T_2 –TE90, DWI and PD) at the acute time point were put into the IC model to produce their corresponding multi-parametric map. The difference between DWI and T_2-Chronic lesions was considered as the penumbra. The power of predicting the core and pattern of the T_2-chronic lesion was used for evaluation of the robustness of the proposed model.

Results and Discussion: As shown in Figure-2, the patterns of the lesions in IC multi-parametric maps (third column) are well matched with their corresponding lesion patterns in the T_2-chronic (second column). Penumbra area would be considered as the difference between the DWI (first column) lesion and the lesion estimated by the multi-parametric map. In this study, an IC model is introduced, derived, formulated, and applied to MR acute information of twelve patients to generate a set of multi-parametric maps. The co-registered three-month T_2 map was considered to be the gold standard for the tissue fate, and its difference from the multi-parametric map and DWI lesion was used to validate the proposed model. Although the other multi-parametric algorithms (K-means and ISODATA) work well for images with clusters that are spherical with the same variance, this is not always true for MR images [3-4]. Thus, an algorithm independent of the distribution of the clusters in image modalities that uses voxel based information can be useful in treatment of stroke. We conclude that an IC model is capable of identifying the ischemic penumbra, both in pattern and size, of a stroke from acute MR information and may describe tissue viability. Since it is strongly related to the clinical outcome, such modeling may play an important role in the assessment of subacute therapeutic interventions, currently of great interest in the treatment of stroke.

References

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