Cerebral Perfusion Measurements by Dynamic Susceptibility Contrast MR and a Gaussian Relaxation Model

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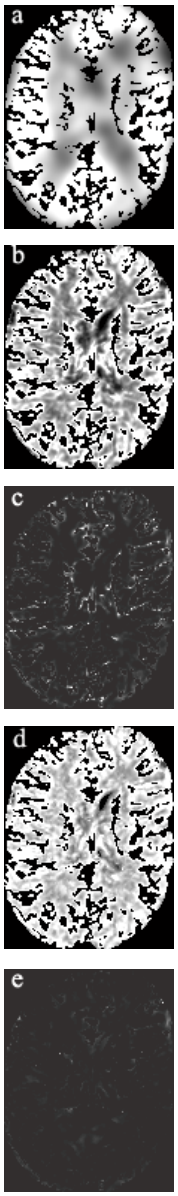


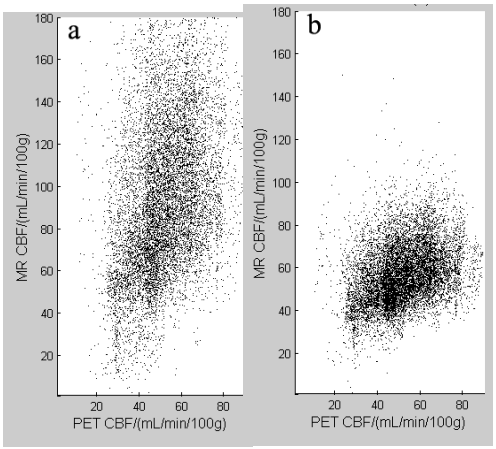
Fig. 1. *Representative* ***(a)*** *PET CBF,* ***(b)*** *MR CBF by existing methods,* ***(c)*** *MR-PET variances for existing methods,* ***(d)*** *MR CBF by Gaussian relaxation theory and* ***(e)*** *MR-PET variances for Gaussian relaxation theory.*

PROBLEM. Regional mismatches between perfusion and diffusion measurements by MR are associated with increased risk of infarction [1-5]. To elucidate the underlying mechanisms by which perfusion MR reveals hemodynamic impairment in stroke, we rederived the standard model of dynamic susceptibility contrast from the point of view of relaxation theory. We found the assumption of linear dependence of the change of effective relaxation rate (ΔR_2^*) on gadolinium concentration ($[Gd^{3+}]$) to be a potential source of error in quantitative MR perfusion measurements [6,7].

THEORY. Relaxation theory suggests that ΔR_2^* may arise from terms quadratic in the concentration of gadolinium [8-11]. Under conditions whereby the diffusive Brownian motion of spins is Gaussian in the vicinity of dynamic susceptibility inhomogeneities, ΔR_2^* is exactly quadratic in $[Gd^{3+}]$. This results from the unique truncation properties of a Gaussian cumulant expansion of relaxation terms. It also follows that ΔR_2^* will be a function of the local tissue diffusion coefficient. Other have experimentally observed that it is the phase of magnetization which is affected by terms linear in $[Gd^{3+}]$ [12]. In fact, the quadratic variation of ΔR_2^* with $[Gd^{3+}]$ has been experimentally observed by van Osch, *et al.*, but we emphasize the generality of the cumulant truncation property [11,9].

METHODS. To test our hypothesis, we re-examined MR and PET perfusion data obtained from nine patients of the St. Louis Carotid Occlusion Study [13]. These patients with chronic, but stable, carotid artery occlusions were studied by MR and PET on the same day. MR data were collected on a Siemens Magnetom Vision using EPI with power injection of gadodiamide dosed to 0.2 mmol/kg. Bolus passages were processed with models linear in $[Gd^{3+}]$ as well as models quadratic in $[Gd^{3+}]$. Numerical deconvolutions were performed using the maximum-likelihood estimation method of Vonken, *et al* [14]. The processed results were then directly compared to PET results obtained by the Kety auto-radiographic method and the cerebral blood flow (CBF) corrections of Herscovitch, et al. [15-17]. PET perfusion measurements were made on an ECAT EXACT HR scanner using boluses of $[^{15}O]$-H_2O.

RESULTS. The Gaussian relaxation theory provides stronger association of MR CBF with PET CBF according to χ^2 merit functions. A representative scatter plot of pixels from a single patient is shown in fig. 2. For statistical analysis, MR pixels were binned in 5mm x 5mm regions so as to match the 5mm Gaussian filtering used in PET processing. The χ^2 merit functions were



538730 and 318383 respectively for linear and quadratic models. The Pearson correlations were respectively 0.950 and 0.971. Spearman correlations respectively were 0.995 and 0.997. Slopes of lines fitted by linear least-squares were respectively 0.52 and 0.93. Slopes improved in the majority of cases which used the quadratic model. The Pearson correlations exceeded 0.886 for all evaluated cases. The Spearman correlations exceeded 0.983 for all cases, with all error probabilities at machine precision. While the distribution of PET CBFs over brain parenchyma was normal, MR CBFs were generally not normally distributed, motivating use of the Spearman rank-order statistics [18].

CONCLUSIONS. Analysis of MR perfusion with cumulant relaxation theory and a Gaussian assumption yields expressions for ΔR_2^* which depend quadratically on $[Gd^{3+}]$ and include the tissue diffusion coefficient. Processing MR perfusion data with both linear and quadratic models showed the quadratic model to yield significant and stronger association with PET results. The results held both for asymptomatic chronic stroke patients as well as symptomatic hemodynamic impaired patients.

Fig. 2*. Scatter plots of PET CBF against MR CBF for an asymptomatic patient: (a) linear model, AIF contralateral to occlusion (b) Gaussian relaxation theory, AIF contralateral to occlusion.*

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