Error propagation in Vessel Size Index Imaging

E. L. Barbier[1,2], S. Valable[1,2], C. Lucatelli[1,2], I. Troprès[2,3], C. Segebarth[1,2], C. Rémy[1,2]

[1]Inserm, U594, Grenoble, F-38043, France, [2]Univ Grenoble 1, Grenoble, F-38043, France, [3]Inserm, IFR1, Grenoble, F-38043, France

Introduction

The vessel size index (*VSI*) provides information on the distribution of vessel radii in a voxel (1). Experimentally, it can be estimated by quantifying the changes ΔR_2 and ΔR_2^* induced by the injection of an intravascular susceptibility contrast agent, the variation of the susceptibility difference between blood and tissue before and after contrast injection ($\Delta\chi$), and the apparent diffusion coefficient (*ADC*). *VSI* is then computed according to the expression $VSI = 0.424(ADC/\gamma\,\Delta\chi\,B_0)^{1/2}\,(\Delta R_2^*/\Delta R_2)^{3/2}$.

The present study aims to characterize the contribution of each of the experimentally derived parameters mentioned above to the error on VSI. This analysis should allow evaluating the smallest change in VSI that can be detected across images in a given experimental protocol. Also, it should be possible to identify the most important directions for acquisition scheme optimization.

Material and Methods

The experimental protocol essentially followed the approach described in (1). Data were acquired on anesthetized (isoflurane, 2%) rats (n=5) bearing a brain tumour. Animals received 200µmol Fe/kg of Sinerem® (Guerbet laboratories). MR images were obtained at 2.35T (SMIS console) on 1mm thick slices with a voxel size of 312x312 µm. Signal value was taken as the average signal intensity over a region of interest (ROI) placed on the normal brain cortex and noise was taken as the standard deviation measured in a ROI drawn on the image background. The analysis of the animal data yielded the ranges of encountered T_2^*, ΔR_2^*, ΔR_2, *ADC*, and *VSI* values. These ranges were used during error propagation. Errors (ε) were computed as follow:

$$\varepsilon(\Delta R_2) = \frac{1}{TE}\left(\frac{\varepsilon S_{before}}{S_{before}} + \frac{\varepsilon S_{after}}{S_{after}}\right)$$

ΔR_2 was computed from the signals of two spin echoes (*TE*=100ms) acquired prior to (S_{before}) and after (S_{after}) contrast agent injection. Since the noise level is not affected by the presence of contrast agent, one expected $\varepsilon(S_{before}) = \varepsilon(S_{after})$.

$$\varepsilon(\Delta R_2^*) = \frac{\varepsilon T^*_{2after}}{(T^*_{2after})^2} + \frac{\varepsilon T^*_{2before}}{(T^*_{2before})^2}$$

ΔR_2^* was computed as the difference $1/T_{2\,after}^* - 1/T_{2\,before}^*$. $T_{2\,before}^*$ and $T_{2\,after}^*$ were obtained from fitting the gradient echo signals collected at TE=[6 12 18 24 30 36 42] ms prior to and after contrast agent; The errors on $T_{2\,before}^*$ and $T_{2\,after}^*$ ($\varepsilon T_{2\,before}^*$, $\varepsilon T_{2\,after}^*$) were obtained by a Monte-Carlo simulation in which signals and noises measured on the first gradient echo images were injected. Errors obtained from the Monte-Carlo simulation were propagated as indicated by the equation on the left to estimate $\varepsilon(\Delta R_2^*)$.

$$\varepsilon(ADC) = \frac{1}{3b}\left(\frac{\varepsilon S_x}{S_x} + \frac{\varepsilon S_y}{S_y} + \frac{\varepsilon S_z}{S_z} + \frac{3\varepsilon S_0}{S_0}\right)$$

The error on *ADC* was computed as shown on the left: S_0 is the signal obtained in absence of diffusion gradient; S_x, S_y, and S_z were obtained in the presence of a diffusion gradient in the x, y, and z directions respectively (b=800s/mm²). Since the noise level is not affected by the diffusion gradients, one expected $\varepsilon S_x = \varepsilon S_y = \varepsilon S_z = \varepsilon S_0$.

A value of 0.57ppm was used for $\Delta\chi$ (1). As a first approximation, we considered that the error on $\Delta\chi$, $\varepsilon(\Delta\chi)$, did not exceed 10% (1).

Finally, the error on *VSI*, $\varepsilon(VSI)$, was obtained by:

$$\varepsilon(VSI) = \left|\frac{\partial VSI}{\partial \Delta R_2}\right|\varepsilon(\Delta R_2) + \left|\frac{\partial VSI}{\partial \Delta R_2^*}\right|\varepsilon(\Delta R_2^*) + \left|\frac{\partial VSI}{\partial ADC}\right|\varepsilon ADC + \left|\frac{\partial VSI}{\partial \Delta\chi}\right|\varepsilon(\Delta\chi)\ ,$$

where expressions for each partial derivative were obtained analytically.

Results

The signal-to-noise ratios obtained in the raw images are displayed in Table 1. As expected, noise levels did not depend on the presence of a diffusion gradient or on the presence of contrast agent. For *ADC*, an error of 5% was obtained. Fig 1b shows that ΔR_2^* is measured with an error smaller than 10% in the range of 10 to 60 s^{-1} (Fig. 1a). The error on ΔR_2 is 9% at best and is less than 15% over a range of 3 to 15s^{-1} (Fig. 1b). Simulations also shows that the relative influence of *ADC* error on *VSI* is half of the relative influences of ΔR_2 and ΔR_2^* errors, which are identical (data not illustrated here). Fig. 1c shows the error on *VSI*, which ranges between 21% and 55%. Since a same value of *VSI* can be obtained from different combinations of ΔR_2^* and ΔR_2, multiple error values are obtained for a single *VSI* value. In Fig. 1c, points highlighted in red (largest errors) can be obtained with a ΔR_2 smaller than 5s^{-1}, which is not measured properly with our approach ($\varepsilon(\Delta R_2)$ greater than 10%, Fig. 1b). These points represent the largest error values.

Parameter	Signal / Noise
For ΔR_2:	
before	34.3
after	23.4
For ΔR_2^* (first echo):	
before	116.6
after	116.4
For *ADC*:	
X	23.4
Y	22.7
Z	26.8
No diff	54.0

Table 1. Signal-to-noise ratios.

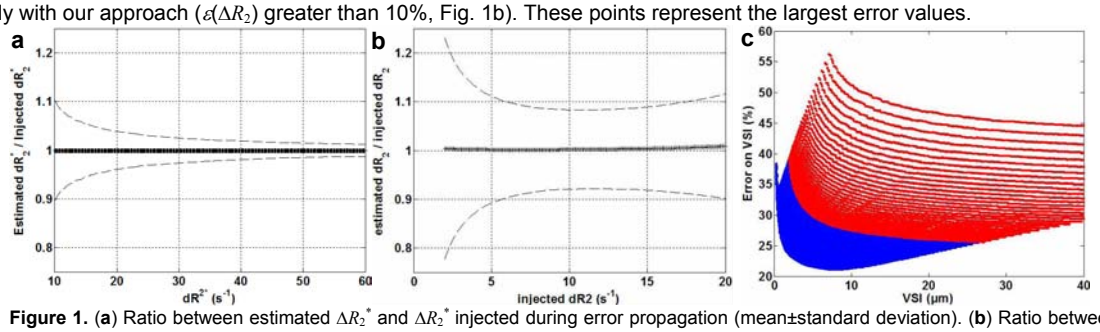

Figure 1. (**a**) Ratio between estimated ΔR_2^* and ΔR_2^* injected during error propagation (mean±standard deviation). (**b**) Ratio between the estimated ΔR_2 and the ΔR_2 injected during error propagation (mean±standard deviation). (**c**) Error on *VSI*. Since numerous combinations of ΔR_2 and ΔR_2^* yield the same *VSI* value, one value of *VSI* is related to multiple errors values. Points in red correspond to values of *VSI* obtained with values of ΔR_2 lower than 5s^{-1}.

Conclusion

VSI quantification could be improved (i) by reducing the first gradient echo times to improve the ΔR_2^* measurement (ii) but mostly by improving the ΔR_2 measurement (e.g. by acquiring multiple spin-echoes), which appears to be the largest contributor to *VSI* error (2). The results also suggest that, in normal tissue where *VSI* ~4.8 µm (1), the smallest *VSI* increase detectable is about 2.4 µm (considering a 25% error and an increase of two times the error). This suggests that *VSI* could be used as an early indicator of tumour angiogenesis.

References

(1) Magnetic Resonance in Medicine, 51:533-541, 2004. (2) Proc. Intl. Soc. Mag. Reson. Med. 11 (2003) #1271.

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