Spatio-spectral Non-linear Filtering of Spectroscopic Imaging: Increasing Signal-to-noise Ratio while Preserving Spatial and Spectral Structures

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Introduction

Spectroscopic imaging (SI) is a powerful tool for biological functional imaging which maps indigenous metabolic molecules and exogenous molecules of contrast agents. However, its low signal-to-noise ratio (SNR) and low spatial resolution sometimes inhibit the detection of small changes in molecular concentrations. With this drawback in mind, we have developed a new spatio-spectral non-linear filter for SI. It increases the SNR while preserving spatial structure and spectral line shape. The filter uses adaptive weighted smoothing which is usually used for two- or three-dimensional MRI data [1,2] or a series of MRI data [3,4]; however, application of the adaptive weighted smoothing to SI has not previously been well studied. We adapted it to SI data by filtering chemical shift direction differently from spatial direction: using adaptive weighted smoothing only in the spatial direction while calculating weight based on spectral similarities in spatial neighborhoods. We also optimized weight allowance, which balances the SNR versus spatial- and spectral-resolution trade-offs, to minimize root-mean-square error (RMSE) estimates. We validated the filter on simulated data and real data of ischemia rat models measured using echo-planar spectroscopic imaging (EPSI).

Methods

The detailed filtering steps are as follows. [Step 1] For each spatio-spectral coordinate (x_0,y_0,c_0), calculate the weight $w(x_n,y_n,c_0)$ of the spatial neighborhood (x_n,y_n,c_0) by the following equation:

$$w(x_0, y_0, c_0, x_n, y_n) = A \cdot \exp\left(-\left| \int \left(f(x_0, y_0, c) - f(x_n, y_n, c) \right) h(c, c_0) dc \right|^2 \Big/ 2kl\sigma^2 \right), \quad (1)$$

where $f(x,y,c)$ denotes the spectrum at (x,y,c), $h(c,c_0)$ is a finite support function that localizes calculation of difference between two spectra around c_0, l is a parameter that adjusts the reduction of noise level by $h(c, c_0)$ averaging noise in chemical shift direction, σ is the standard deviation of noise, and k is the weight allowance, which balances SNR versus spatial structure. High value of k increases the SNR but distorts spatial structure, and low ones do nothing to the SNR or spatial structure. [Step 2] Calculate $w(x_0,y_0,c_0,x_n,y_n)$ for all spatial neighborhoods (x_n,y_n) around (x_0,y_0) (including (x_0,y_0) itself), and calculate $w'(x_0,y_0,c_0,x_n,y_n)$ as the ratio to the sum of all $w(x_0,y_0,c_0,x_n,y_n)$. [Step 3] Set a filtered spectrum $f'(x_0,y_0,c_0)$, as the weighted average of $w'(x_0,y_0,c_0,x_n,y_n) \cdot f(x_n,y_n,c_0)$. These steps enable the preservation of a spatial boundary of each molecular distribution. If there is a spatial boundary between (x_0,y_0) and (x_2,y_2) of which spectral difference around c_0 is large enough, then $w(x_0,y_0,c_0,x_2,y_2)$ becomes lower and $f(x_2,y_2,c_0)$ is not added to $f(x_0,y_0,c_0)$ at all (Fig. 1).

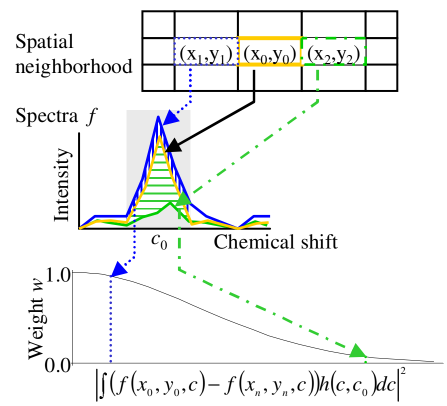

Fig. 1. Diagram how weight w is calculated.

We tested the filter and found the optimal weight allowance value k by using simulated data. The data was created by adding Gaussian noise to original data. We used (a) unfiltered data, and data filtered using (b) standard spatial smoothing and (c) our filter with various k values and calculated RMSE between the filtered and the original data. We also tested the filter by using real SI data of rat ischemia models. The data was obtained using a 4.7-T MRI system and ^{1}H EPSI about three hours after an onset of right focal cerebral ischemia [5]. We applied the same filter to these data as to the simulated data. When we applied our filter, the standard deviation of noise was calculated at corners where no molecular concentrations are. The weight allowance k was set to 4, which was found to be the optimal value from the experiment on the simulation data.

Results and Discussion

The results from the simulated data show that our filter lowered RMSE than the other filters, and the minimum RMSE for it was achieved around $k = 4$ (Fig. 2). The filtered data show that our filter increased the SNR, and preserved spatial borders and spectral line shape (Fig. 3). The filtered data on ischemia rat models show that our filter increased the SNR more than the value of the unfiltered data and preserved spatial structure better than the standard spatial smoothing (Fig. 4). The figure clearly shows that due to our filter, N-acetylaspartate (NAA) concentration in the right hemisphere was lower than that in the left, which was induced by ischemia.

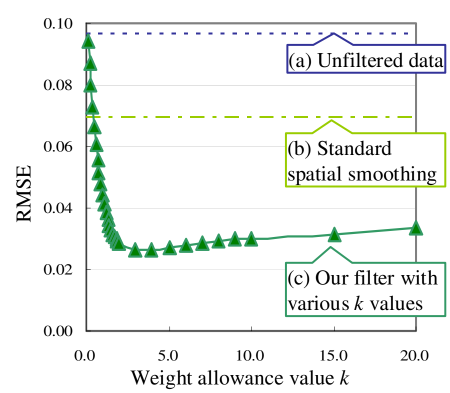

Fig. 2. RMSE vs. weight allowance value k for our filter. RMSE values of (a) unfiltered data and (b) data filtered using the standard spatial smoothing are overlaid.

Conclusion

We developed a new spatio-spectral non-linear filter for SI, which uses the adaptive weighted smoothing in the spatial direction and calculates the weight based on the spectral similarities. The results show that choosing appropriate parameters in the filter improved the SNR, while it preserved spatial structure and spectral line shape.

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References

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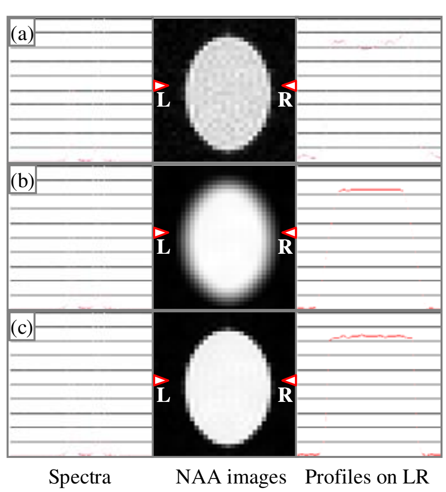

FIG. 3. Filtered simulated SI data.

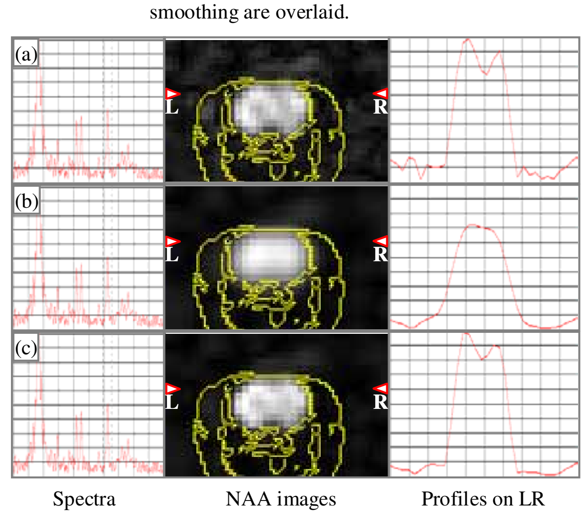

FIG. 4. Filtered real SI data of a ischemia rat model.