Application of Iterative Deconvolution Methods for Optical Coherence Tomography Imaging

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Abstract: The axial resolution of Optical Coherence Tomography (OCT) images depends on the spectral bandwidth of the optical source. By enhancing the image sharpness through deconvolution, we can enhance the resolution of the OCT images. Iterative algorithms allow performing this in a convenient computing time. Using these algorithms, we demonstrate how to overcome the spectral bandwidth limit of the resolution in OCT systems.

OCT is a novel technology for medical imaging applications that provides high resolution(a few ㎛) cross sectional images of biological specimens in a non destructive and non invasive way. This system is based on a Michelson interferometer with an oscillating mirror in one arm and a sample in the other. The oscillations of the mirror provide interferometric data for different depths inside the sample. A two dimensional or cross sectional image of a sample can be obtained by translating the illuminating end of the fiber across the sample. Due to the absorption of the light by the tissues, the required laser source power is about a few ㎽ to provide an image of a 2 mm depth. Also, a wide spectral bandwidth is needed, as the resolution is inversely proportional to this parameter. Since broadband and high power sources are expensive, we can use the signal deconvolution technique to overcome the resolution bottle-neck due to the limited bandwidth of the source.

We can describe OCT with a Linear Shift Invariant (LSI) model under some suppositions[1]. The LSI suppositions allow us to consider the output of the OCT system y as the convolution of the information acquired from the sample function x and the system impulse response function h. Usually, h is mostly the consequence of the narrowness of the spectral bandwidth. Note that in this model, h is 1-dimensional depending on the length difference between reference and sample arms (Δl).

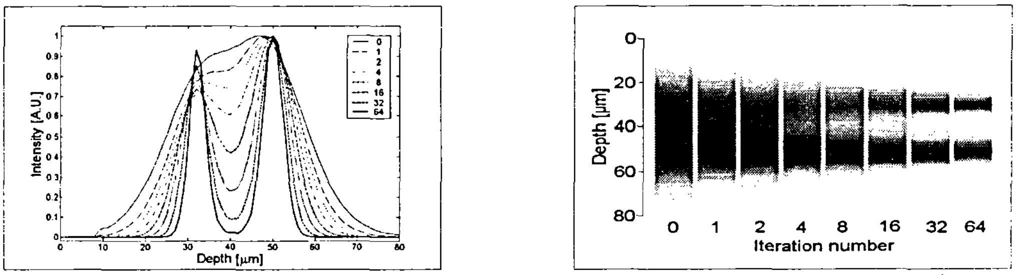
$$y(\Delta l) = x(\Delta l) \otimes h(\Delta l) \qquad (1)$$

Solving this equation directly using Fourier Transform would result in a huge contrast loss in most cases, this is why we resort to iterative deconvolution methods. In our case, we will not need to use blind deconvolution methods, as it is possible to get an estimate of the impulse response using a mirror. Since a mirror has a single reflection point, we can set the sample function for the mirror as $x_{mirror}(\Delta l) = \delta(\Delta l)$, which gives

$$y_{mirror}(\Delta l) = x_{mirror}(0) \otimes h(\Delta l) = \delta(0) \otimes h(\Delta l) = h(\Delta l) \qquad (2)$$

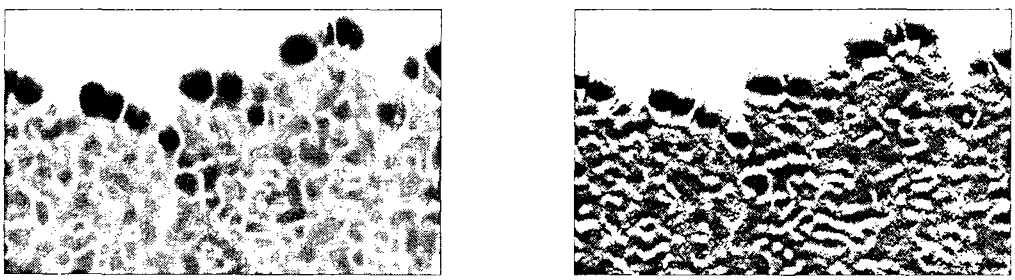
Let's set the system output function of a sample as $y_{sample}(\Delta l)$. Then, iterative deconvolution methods provide successive estimations $x_k(\Delta l)$ converging toward the solution of eq. (1). In most algorithms, the initial sample function is set as the system output function, $x_0(\Delta l) = y_{sample}(\Delta l)$. Then a process of $x_{k+1}(\Delta l) = f(x_k(\Delta l))$ is applied until the error between the two successive solutions of eq. (1) gets low enough. The function f depends on $y_{sample}(\Delta l)$ and $h(\Delta l)$. Many methods for the deconvolution have been developed; such as *Van Cittert's method[2]*, *constrained method[3]*, *relaxation-based method[2]*, *Jansson's method[4]* and ratios based algorithms, as *Gold's ratio method[2]* and *Richardson-Lucy method[4]*.

Fig. 1 represents the 1-D OCT image of an air gap surrounded by two glass surfaces, which is deconvoluted by the Gold's ratio method. The figure shows that the two surfaces of the air gap, that could not be distinguished in the original system output, becomes distinguishable as increasing the number of iterations. Note that in real situation, a number of iterations between 8 and 16 is enough to provide good results. Fig. 2 represents the deconvolution of an OCT image (acquired with a 15 ㎛ axial resolution) of a complex biological sample (mouse duodenum). The same iteration algorithm was used. It gave about two times improvement in the axial resolution and induced a limited loss of contrast.



(a) 1-dimensional acquisition (graph representation) (b) 2-dimensional acquisition (gray map)

Fig. 1 One dimensional OCT images of an air gap between two slide glasses obtained by doing 0, 1, 2, 4, 8, 16, 32, 64 iterations of the Gold's Ratio algorithm.



(a) Before deconvolution (b) After deconvolution

Fig. 2 Two-dimensional OCT images of mouse duodenum (size : 1200 x 400 ㎛, resolution : 2 x 15 ㎛, log- scale gray map) before(a) and after(b) 16 iterations of the Gold's Ratio algorithm.

Due to lack of information concerning the solution, the *Van Cittert's* algorithm creates many artifacts. The *Constrained* and the *relaxation based* algorithms provide good results fast because they already "know" that the solution is positive, but must be used carefully because they cause data loss. The *Jansson's* algorithm is only useful for situations where the sample gives similar intensities along the depth, which is rare in OCT. The *Gold's ratio* algorithm is very fast but is only reliable when the signal-to-noise ratio (SNR) is low, while the *Richardson-Lucy* algorithm is slow but stable even for high SNR. As a conclusion, we can say, for OCT applications, it is preferable to use the *constrained*, the *relaxation*, or *Gold's ratio* method for a high SNR case and the *Richardson-Lucy* -method is good for a low SNR case.

References

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