Fully Automated Gating of Optical Coherence Tomography Data

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Abstract

Intra-coronary optical coherence tomography (OCT) provides ultra-high resolution imaging of coronary vessel wall structures. However, during image acquisition the OCT catheter is affected by cardiac motion. These motion-induced artifacts not only complicate longitudinal image reconstructions, it results in a saw-tooth shaped appearance of the coronary vessel wall, but more importantly it affects the accuracy of quantitative analysis (QOCT). To overcome this problem we propose to perform image-based gating applying a genetic algorithm (GA) that automatically selects a subset of OCT cross-sections that are relatively unaffected by the catheter displacement during the cardiac cycle. The gated subset contains cross-sections (frames) acquired in the near end-diastolic phase, during which the heart is relatively motionless. We evaluated the GA in a comparison test with a different gating method (Simulated Annealing (SA)) and with manual frame selection (MFS) and found promising results.

1. Introduction

Optical coherence tomography (OCT) is a new intra-coronary imaging technique capable of cross-sectionally imaging the coronary arteries at high image resolution, close to that of histopathology. This resolution is much higher than that of intra-coronary ultrasound (ICUS) the current de-facto reference intra-coronary imaging method and shows much more morphological details. For later quantitative analysis, especially within studies evaluating new treatment methods, the lumen areas and consequently lumen volumes are measured. The current standard method for quantitative OCT analysis involves manual selection of frames at fixed distances, since analysis of all frames (several hundred per patient) is impractical. This method is referred to as the manual frame selection (MFS). However, cardiac motion induced catheter displacement could cause a reduced quantification accuracy. The motion effects appear as a saw-tooth shaped representation of the coronary vessel wall in reconstructed longitudinal views, which are often used during quantification. Within the MFS method the time interval between the manually selected frames is 1-to-1 translated to distance; however, this assumption is incorrect as longitudinal catheter motion influences the distance (and thus the anatomical position) between the locations where the frames are acquired. Furthermore, during the cardiac cycle the vessel dimensions vary, under influence of the blood pressure, where the MFS does not account for as the frame selection is random with respect to the cardiac cycle. Therefore, the accuracy of the coronary dimensions as quantified by MFS is diminished. By applying gating, these problems may be prevented, analogous to what has been proposed for ICUS previously [1].

2. Materials

OCT imaging was performed with a commercially available system (Lightlab imaging, Westford, MA, USA). This system uses a 1310-nm broadband light-source generated by a super luminescent diode with an output power of 8.0mW. The average tissue penetration depth is approximately 1.5 mm with an axial and lateral resolution of 15 μm and 25 μm, respectively. The imaging probe has the size of a guide-wire with a maximum outer diameter of 0.019 inch (Imagewire^{TM}, LightLab Imaging). The wire contains a single-mode fibre optic core within a translucent sheath. It is connected to an imaging console, similar to ICUS, that is responsible for real-time image data processing, visualization and image storage. Systematic imaging of a coronary segment is also similar to ICUS by an automatic continuous speed pullback (between 1 and 3 mm/s) of the imaging wire. OCT images are generated at a rate of 5-20 per second (ICUS 30 frames/s).

3. Automated image-based OCT gating

Image-based gating methods rely on information retrieved from the images themselves (e.g. called features). Retrospective image-based gating methods are feasible as has been published for ICUS [1]. Unfortunately, the approach used for ICUS cannot be applied for OCT, mainly due to the fact that there are much less details of the coronary wall visible because the tissue penetration depth of

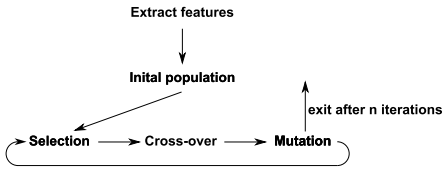

Figure 1. Overview of the genetic algorithm.

OCT is limited to the first 2- to 3 mm (ICUS approximately 9 mm). However, due to the excellent discrimination of the lumen-intima interface, the lumen contours can be automatically detected [2], which is currently not possible for ICUS. Feature information derived from the automatically detected contours compensates for this: lumen areas, centroids, smoothness between selected "gated" frames and the time-distance between them. The development environment selected is Matlab (The Mathworks, Natick, MA, USA).

The gating problem is approached as a multi-dimensional optimization problem which can be solved by a genetic algorithm (GA). The OCT frames are represented as a string of bits in which the assumed end-diastolic frames are labeled as ones and all others as zeros. For each patient data-set, the genetic algorithm generates a number of random selections. Each of the random selections can be seen as an individual, and the group of individuals as a population. The genetic algorithm then simulates evolutionary processes with this population as the first generation. After a number of generations where mutation, mating, reproduction and natural selection are all simulated, the end-result is a individual which by some measure of fitness, also called the fitness function, is the most suitable or the "best" selection. In fig. 1 an overview of the proposed gating algorithm is shown. The steps are described in more detail below.

3.1. Representation of individuals

As above-described, the individuals in a population are represented as a string of bits being 1 (end-diastolic) or 0 (others). This representation provides the following advantages over a list of integers:

1. All selected frames are automatically sorted.
2. A frame can only be selected once.
3. The length of the selection is always constant, which greatly simplifies the GA implementation.

3.2. Fitness function

The fitness function is applied to calculate the "quality" of the frame selection, in which a higher value indicates a better selection. The applied fitness function calculates a weighted mean based on all the features used by the GA. One of the crucial features to determine the success of this algorithm is the time-distance between the presumed end-diastolic frames. The target time-distance is the number of frames per cardiac cycle. The closer the selected frames are to the end-diastolic frames, the better the frame selection match the target-time distance. The target time-distance is estimated as described by O'Malley et al. [3].

Multiple subpopulations

The fitness function applied to the data-set can be described as a landscape. Within this landscape the GA could get stuck in a local optimum and not find the global optimum that we are looking for. To overcome this potential problem, different subpopulations with different selection pressures are used to explore the landscape as defined by the fitness function. Every n^{th} generation individuals are swapped between the subpopulations. This implementation of the GA is based on the work of Hu et al. [4].

Implementation

A GA starts with the creation of an initial population in which every frame of every individual is selected with a probability of $P = \frac{1}{D}$ (where D = target-time distance as measured (Fig. 2)). Due to the evolutionary nature of the GA this can costs considerable amounts of computational time. To reduce this, one specific individual is added that is estimated to be close to the global optimum (e.g. a subpopulation where all the lumen areas of the selected frames are locally minimal (Fig. 2)).

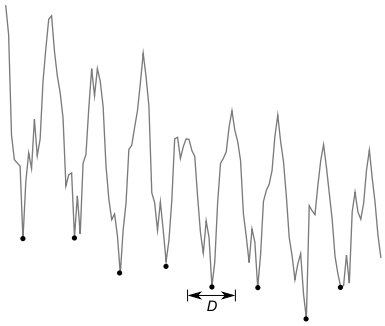

Figure 2. The selected frames where the lumen areas are locally minimal. The distance D is measured in frames per cardiac cycle.

The cross-over operation allows the GA to take the best parts of individuals to create better individuals for the next generation of the population. A tournament selection method is applied to select the parents to produce the next generation. Diversity of a population is required to converge towards a (local optimum). Mutation can be used to create this diversity of the genetic material. The parents

for the cross-over step need to be selected to produce offspring, the individuals of the next generation for which a tournament selection is used.

The best solution found did not improve after 25.000 generations and therefore this number is chosen as a threshold to terminate the GA with the best individual as the final result.

4. Tests and Statistical analysis

To test the proposed implementation of the GA, simulated annealing (SA) is used as a technical reference method [5]. SA is a generic probabilistic meta-heuristic for the global optimization problem of applied mathematics, namely locating a good approximation to the global minimum of a given function in a large search space. It is often used when the search space is discrete (e.g. the selections of cross-sections of OCT data-sets). SA can be thought of as GA with the population of size one having only mutation and no cross-over. SA may or may not perform better than GA for some problems.

Twenty randomly selected OCT cases of patients participating in different studies were used for the tests. Comparisons between the methods are performed by measuring the noise found in the results of these methods in the test sets. Despite our efforts, the GA may not find the global optimum and due to its stochastic nature find a different optimum every time it is executed. The noise of a selection method can be mathematically described as follows:

$$\text{noise} = \frac{\max(L) - \min(L)}{\min(L)}$$

where L are the mean lumen areas for multiple selections of an OCT data-set. To evaluate how the gating method performs if applied clinically, a comparison is made to analyses performed by the MFS method. The MFS method may introduce variability caused by the observer freedom to select a start frame to start the analysis with. The frames which are then analysed are acquired randomly throughout the cardiac cycle and thus may show different areas. To examine this influence, in the test population every single OCT frame was automatically analysed. Frames were then selected at fixed distances from these analyses simulating the standard MFS analysis. With 20frames/s this would result in 20 analyses of which the one with the minimum deviation to the gated result is called best match and with the largest deviation the worst match.

5. Results

From the 20 data-sets, 12 could be retrospectively gated (see fig. 3 for an individual example) in approximately 30 minutes computational time per data-set.

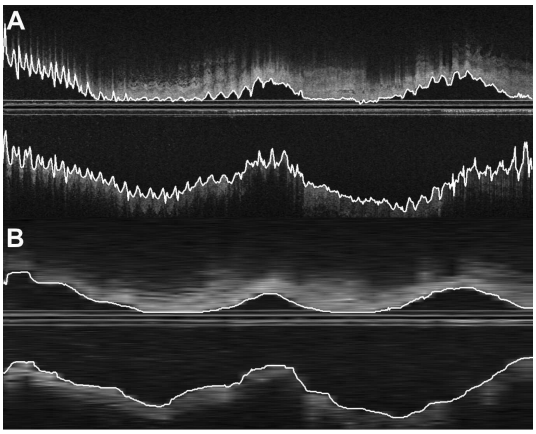

Figure 3. L-view of an OCT data-set before and after gating.

Gated OCT datasets show smooth longitudinal representation (Fig. 3B) of the coronary vessel in contrast to the saw-tooth shaped appearance of non-gated OCT (Fig. 3A). The 8 data-sets that could not be gated showed all a reduced amount of this typical saw-tooth shape, indicating that motion-induced artifacts were minimal for them.

The comparison of the implemented GA method against the SA method, showed that the noise in the GA method is in most cases lower. To evaluate the consistency of the algorithms, five runs of both the GA and the SA method were performed per patient and the results are presented in figure 4, together with the results of the MFS method in which the start frame selection is varied. It can be appreciated that the gated results show the lowest noise levels.

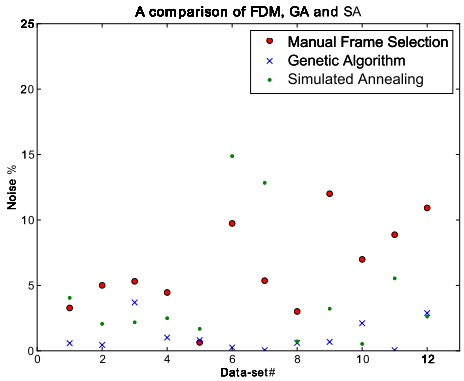

Figure 4. The noise levels of all three methods.

Comparing the gated method to the MFS method showed a relative difference of 5% ($p<0.001$), for both lumen areas and volumes (best match). The worst match selection showed a relative difference of 11% for areas and 22% for volumes (both $p<0.001$). To illustrate the mechanism causing these differences vs. the gated analysis into more detail, an individual case is presented (Fig. 5).

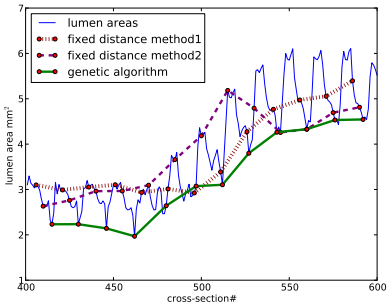

Figure 5. The lumen areas of a single data-set and the result of two MFSs analyses starting at a different frame vs. the gated result.

The lumen areas are presented on the y-axis and the individual frames are on the x-axis. Two possible MFS results are presented as dashed lines and that of the gated analysis as the solid bottom line. This figure illustrates the possible variability in measuring lumen dimensions randomly during the cardiac cycle and thus the dependency (or better said the reproducibility) of the quantitative results by selecting a different start frame when applying the MFS method.

6. Discussion

The proposed image-based OCT gating method works in cases where the imaging catheter is affected by cardiac induced motion. The quantitative differences against the current clinically applied analysis method are significant. These findings should be taken into account if time-domain quantitative OCT parameters are used as surrogate endpoints in studies evaluating new coronary therapies. The findings of gated OCT are in-line with those previously presented for ICUS [6]. The lower success rate to perform gating as compared to ICUS is mainly due to the much lower image acquisition rates of the 1st generation OCT systems (minimum of 5 frames/s up to a maximum of 20 frames/s). This results in data-sets with fewer cross-sections acquired in the near end-diastolic phase, since at a frame rate of 5 frames/s, images are acquired with time gaps between frames of 200ms. These gaps are too large to acquire images close to the relatively short end-diastolic moment. Furthermore, since the imaging-probe for OCT is a wire, it sticks more easily to the coronary vessel wall and might be influenced less by the cardiac motion as compared to the relatively larger and less flexible ICUS catheters. Contradictionally the more motion artifacts are present, the better image based-gating methods seem to perform. To proof clinical usefulness of the proposed method studies incorporating larger number of patients are required.

7. Conclusion

Retrospective image-based time-domain OCT gating in the presence of motion induced artifacts shows promising results. Significant changes in coronary lumen dimensions during the cardiac cycle were observed by OCT and in consequence, gated QOCT analysis showed significant differences compared to non-gated QOCT analysis.

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