# Quantitative Analysis of Circumferential Plaque Distribution in Human Coronary Arteries in Relation to Local Vessel Curvature

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## Background

- Symptomatic coronary artery disease and atherosclerosis are among the leading causes of death in many countries.
- Inter-relationships between vessel geometry, hemodynamics, and plaque development need to be understood.
- 3-D Fusion of x-ray coronary angiography and intravascular ultrasound (IVUS) data allows a geometrically correct representation of coronary geometry and cross-sectional morphology.
- Computational fluid dynamics (CFD) methods are well established to determine shear-stress patterns along the lumen/plaque boundaries.

## Motivation

- It has been observed that plaque tends to accumulate on the inner curvature rather than on the outer curvature of a vessel (Figure 1).
- Simulations in idealized tubular phantoms of constant curvature indicate lower wall shear stress on the inner curvature (Figure 2).
- Given that low wall shear stress is associated with plaque development, can a direct relation between local curvature and circumferential plaque distribution be shown in vivo?

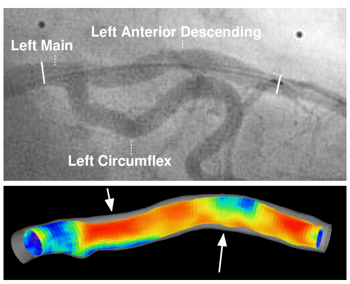



*Figure 1: Coronary angiogram and 3-D reconstruction with plaque included by color coding – arrows indicate plaque accumulation on the inner vessel curvature*

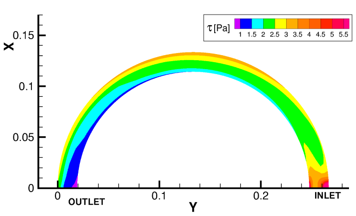



*Figure 2: Shear-stress distribution in an idealized curved tube phantom – low shear stress coincides with the inner curvature of the tube.*

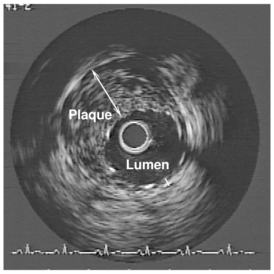



*Figure 3: IVUS image showing eccentric plaque.*

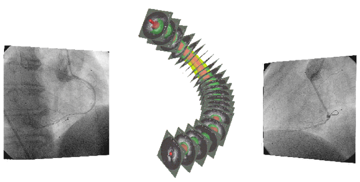


*Figure 4: Example of a 3-D reconstructed fusion model*

## Methods

### (a) 3-D Fusion

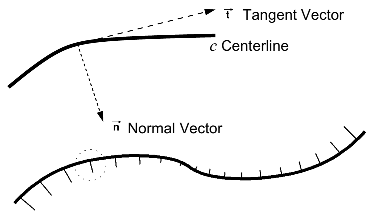
- Lumen/plaque and media/adventitia contours are segmented semi-automatically from the IVUS data, as acquired with end-diastolic gating.
- The IVUS catheter path is determined from the angiograms and reconstructed into 3-D space.
- Fusion yields the final 3-D model (Figure 4).

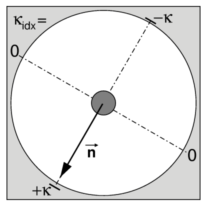
### (b) Plaque Thickness

- Contours resulting from 3-D fusion are initially oriented relative to the catheter.
- Thus, contours are resampled with respect to the vessel centroid, forming a reliable centerline over all frames.
- Plaque thickness is measured along 72 radial lines originating from each centroid as the 3-D Euclidean distance between the contours.

### (c) Curvature Index

- The local curvature index combines two parameters for each contour point:
  1. The magnitude of the local vessel curvature;
  2. The circumferential position of the contour point relative to the curvature direction.
- Directly derived from curvature as defined in differential geometry (Frenet-Serret formulas; Figure 5, next column).




$$\begin{aligned} \vec{c}\,''(s) &= \vec{t}\,'(s) \\ &= \kappa(s)\,\vec{n}(s) \\ \kappa(s) &= \|\vec{c}\,''(s)\| \\ \vec{n}(s) &= \vec{c}\,''(s)\,/\,\kappa(s) \end{aligned}$$

*Figure 5: Curvature and local curvature index*

- The curvature index $\kappa_{idx}(s,i)$ of $i$–th contour point $f(s,i)$ in frame $s$ depends on the vector $v$ from the local centroid $c$ to $f$, and the curvature vector:

$$\begin{aligned} \vec{v}(s,i) &= \vec{f}(s,i) - \vec{c}(s) \\ \kappa_{idx}(s,i) &= \kappa(s)\,\vec{n}(s) \cdot \left( \frac{\vec{v}(s,i)}{\|\vec{v}(s,i)\|} \right) \end{aligned}$$

- Positive $\kappa_{idx}$ indicates <u>*inner*</u> curvature;
- Negative $\kappa_{idx}$ indicates <u>*outer*</u> curvature;
- Maximum absolute $|\kappa_{idx}|$ corresponds to $\kappa$ in $s$.

### (d) Classification of Regions

- From step (b), an average plaque thickness is calculated for each frame; each contour point is labeled with $a$ for plaque thickness above and $b$ for below that average.
- From step (c), each contour point is labeled with $i$ for inner and $o$ for outer curvature; any point for which $|\kappa_{idx}|$ is less than a threshold $T$ is marked with $n$ for neutral.
- This process yields five regions.

### (e) Hypothesis Test

- If regions $R_{ai}$ and $R_{bo}$ combined outweigh regions $R_{bi}$ and $R_{ao}$, it is shown that more plaque accumulated on the inner curvature:

$$r = \frac{\|R_{ai} + R_{bo}\|}{\|R_{ai} + R_{ao} + R_{bi} + R_{bo}\|}$$

$$r \geq 0.5 \quad \text{implies} \quad \|R_{ai} + R_{bo}\| \geq \|R_{ao} + R_{bi}\|.$$

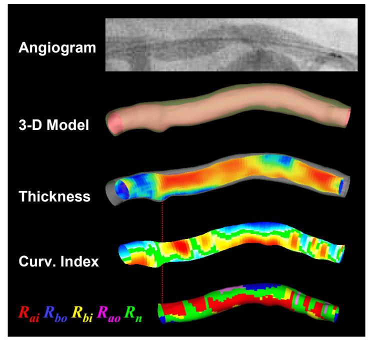



*Figure 6: Results from the vessel shown in Figure 1*

## Results

- 39 in-vivo pullbacks acquired in 37 segments.
- 12 different curvature thresholds $T$ were applied.
- Bifurcations and strong calcifications excluded.
- $r \geq 0.5$ for $\geq 6$ out of 12 $T$-values in 29 segments.
- $r \geq 0.5$ for *none* of 12 $T$-values in 6 segments.
- Average $r$ increases with threshold $T$, indicating the relationship increases with curvature:

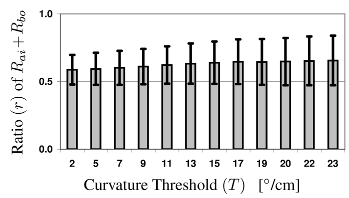



*Figure 7: Dependence of r on T*

## Conclusions

- 3-D fusion methodology based on x-ray angiography and IVUS can be used to quantitatively analyze circumferential plaque distribution and local vessel curvature.
- In the majority of vessels, plaque tends to accumulate on the inner curvature rather than on the outer curvature.
- In vessels with non-trivial geometry or which are located in lower branching levels, the resulting complex flow and plaque-accumulation patterns require more detailed CFD analyses.

## Contact

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