Automatic coronary lumen segmentation with partial volume modeling improves lesions' hemodynamic significance assessment

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Coronary Artery Disease

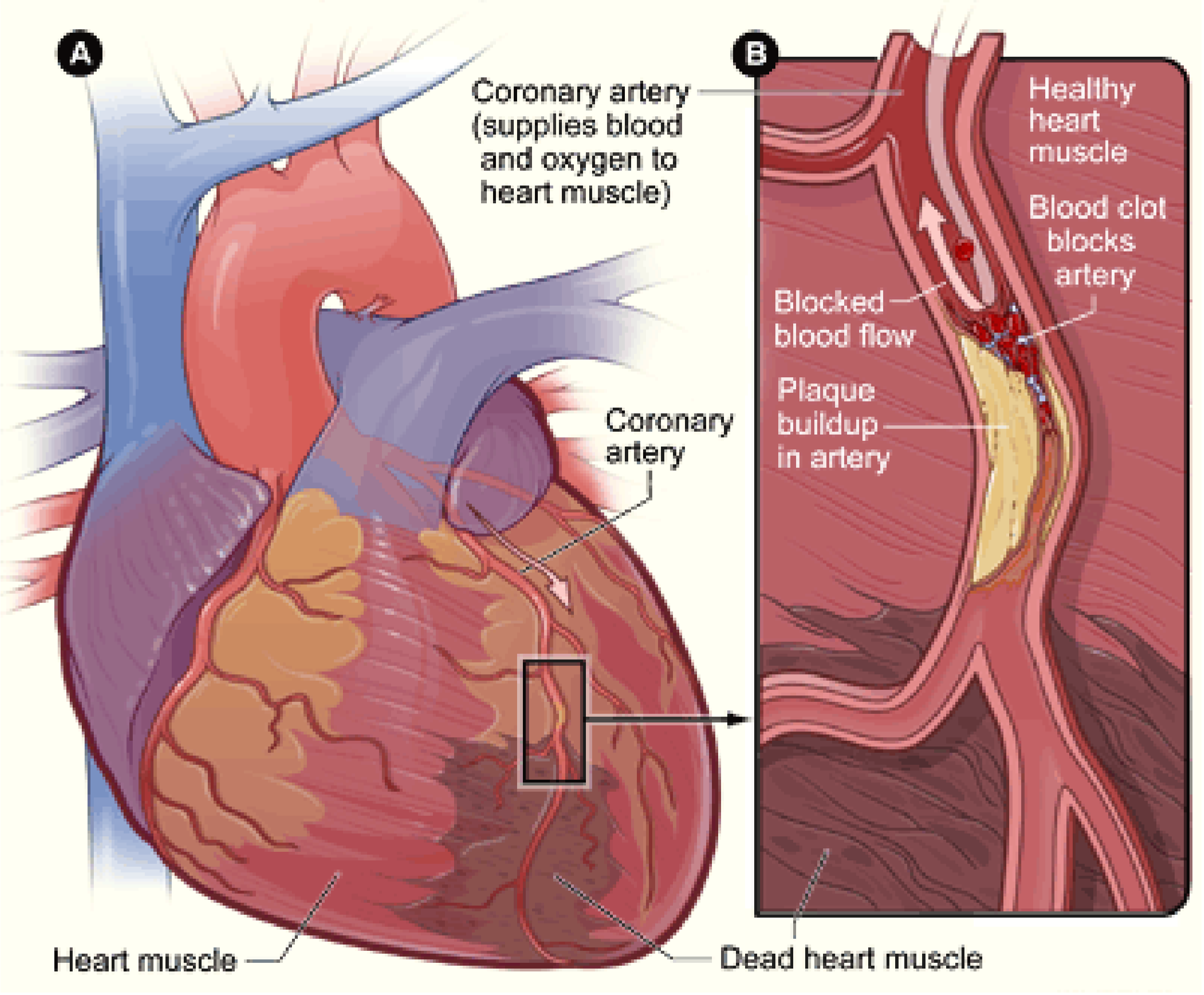
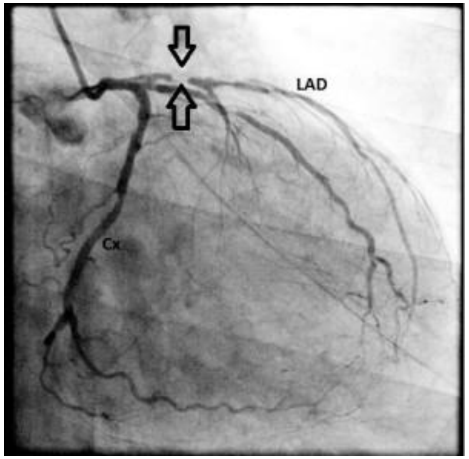
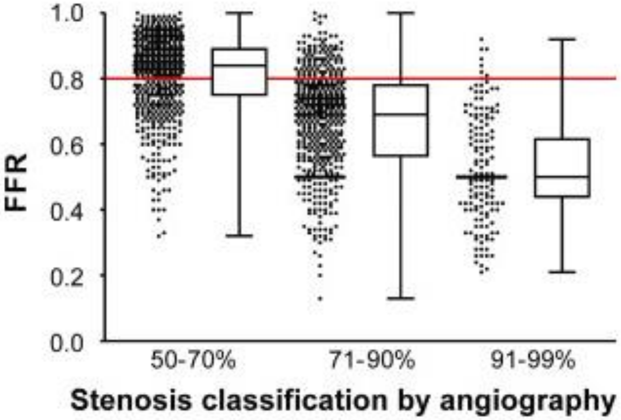


Image source: http://www.nhlbi.nih.gov/health/health-topics/topics/cad/signs

Clinical motivation: from anatomy to function

- Current gold standard for CAD stenting: hemodynamic significant stenosis (i.e. pressure drop (FFR) below 0.8).





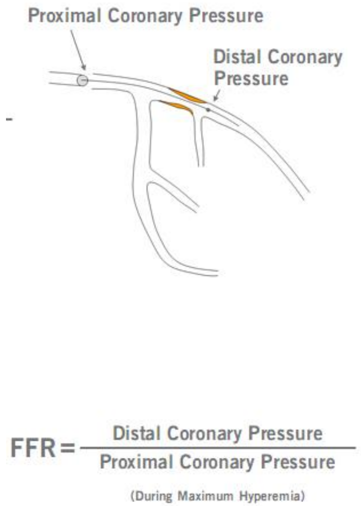


Image sources:

1. http://westjem.com/case-report/red-flags-in-electrocardiogram-for-emergency-physicians-remembering-wellens-syndrome-and-upright-t-wave-in-v1.html
2. Tonino et al, JACC 2010;55:2816-21

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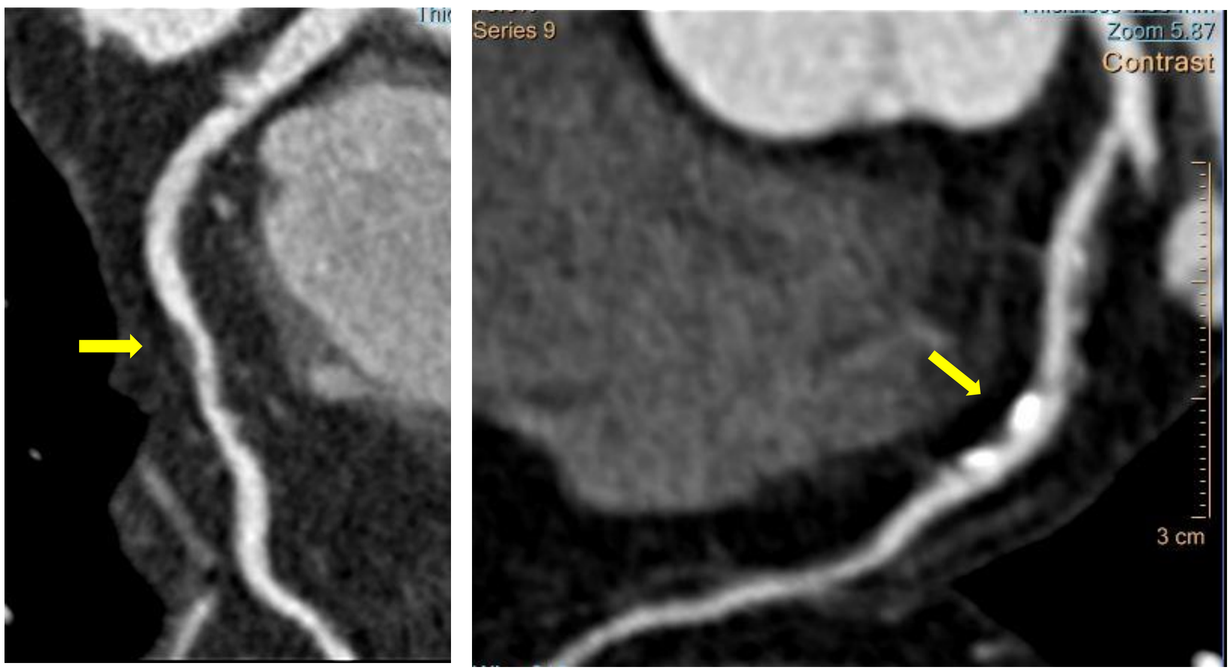
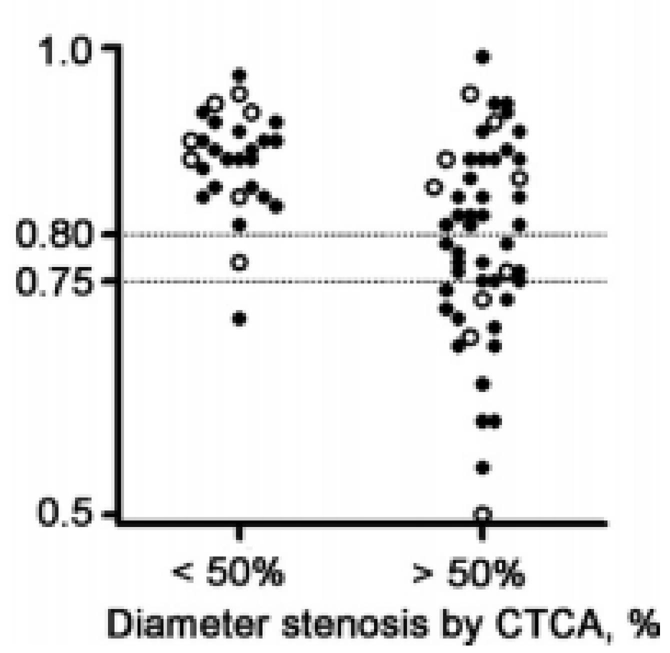
CCTA for Coronary Artery Disease

- Coronary CTA has a high sensitivity and high negative predictive value for diagnosis of obstructive CAD by detecting anatomical narrowing in the coronaries



Anatomical assessment of lesion's significance with CCTA is not enough

- CCTA is currently limited to anatomical information about luminal narrowing in the coronaries



>50% of lesions with greater than 50% diameter stenosis by CCTA have FFR>0.8

Image source: Meijboom et al. J Am CollCardiol 2008;52:636–43

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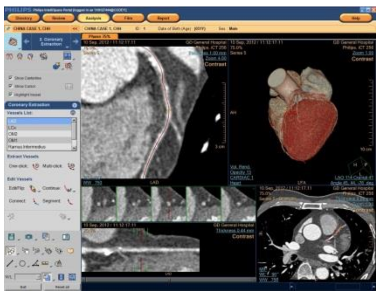
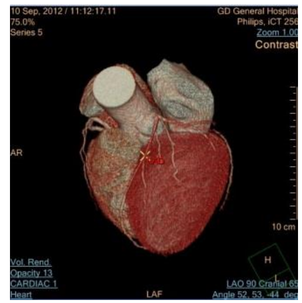
Flow simulation enable lesion's hemodynamic significance assessment from CCTA

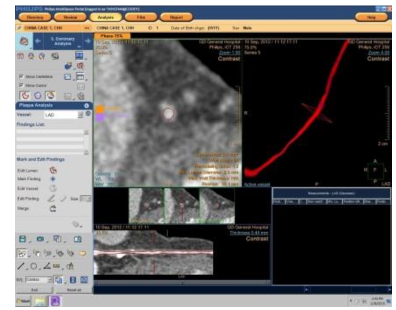
CCTA data



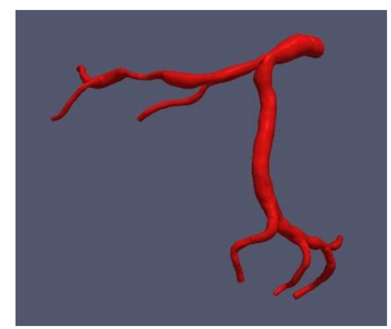
Tree extraction



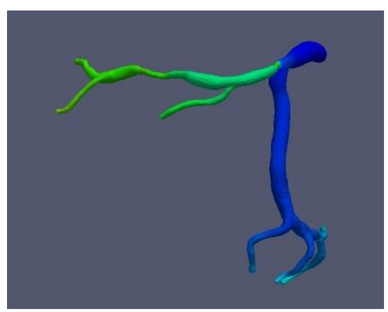
Vessel by vessel segmentation



3D model



CFD simulation



Goal: to improve CCTA specificity by enabling non-invasive CCTA-based functional hemodynamic characterization of coronary stenosis

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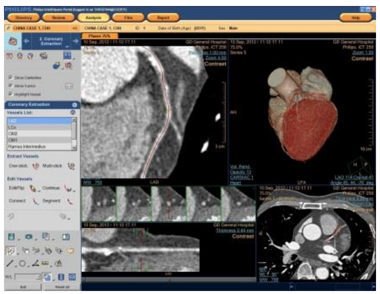
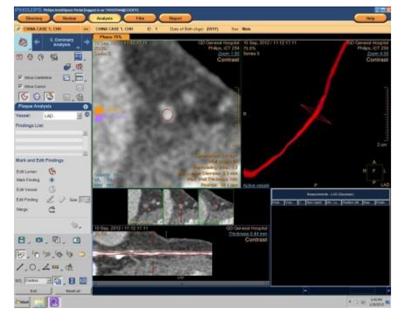
Key enabler of accurate CCTA flow simulation:
Accurate Automatic Coronary lumen segmentation

ISP CCA

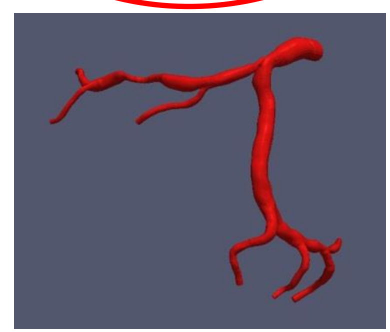


Tree extraction

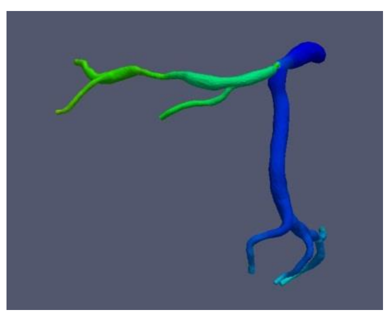
Vessel by vessel segmentation



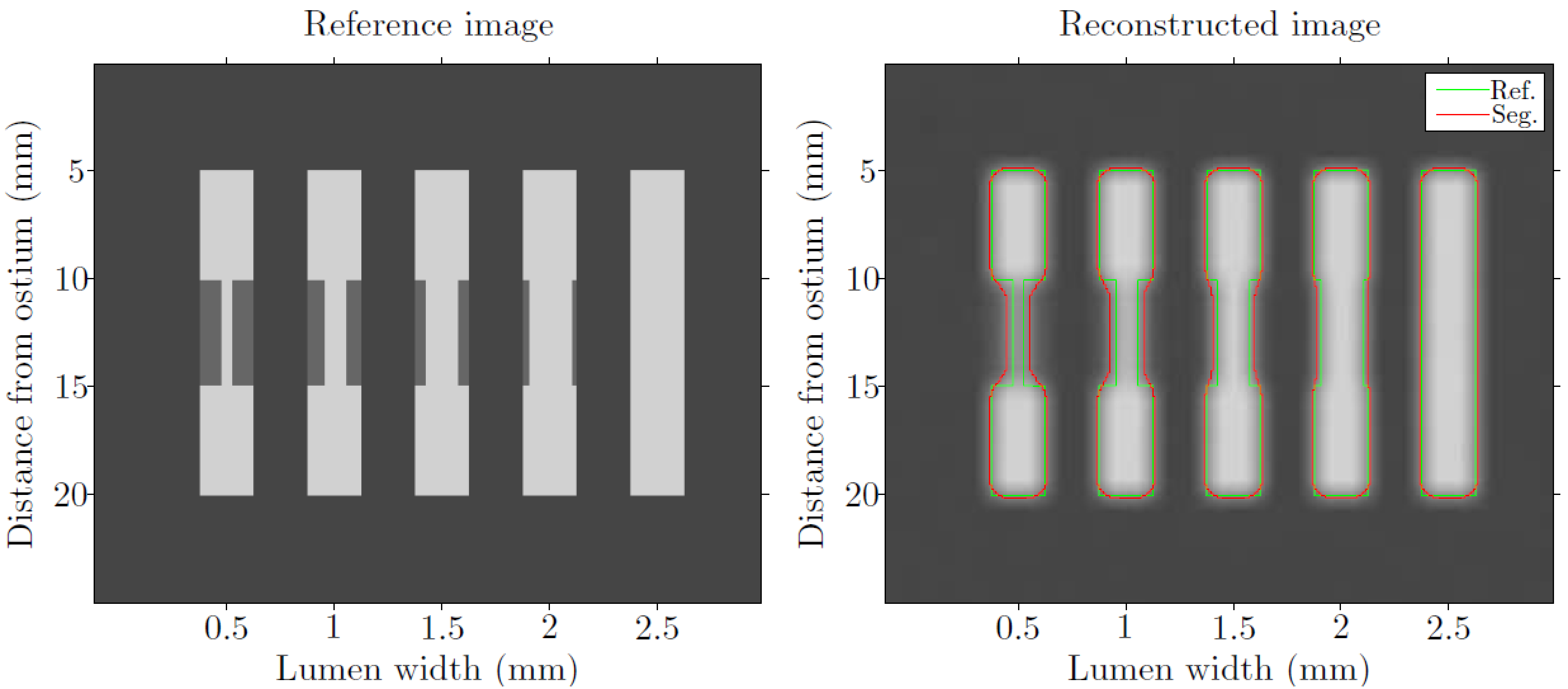
3D model



CFD simulation



Partial volume effect on small-radius vessels



Small vessel diameters can be overestimated due to the overall system PSF[1] and **significantly impact flow simulation results**

1. Sato et all, MICCAI 2004

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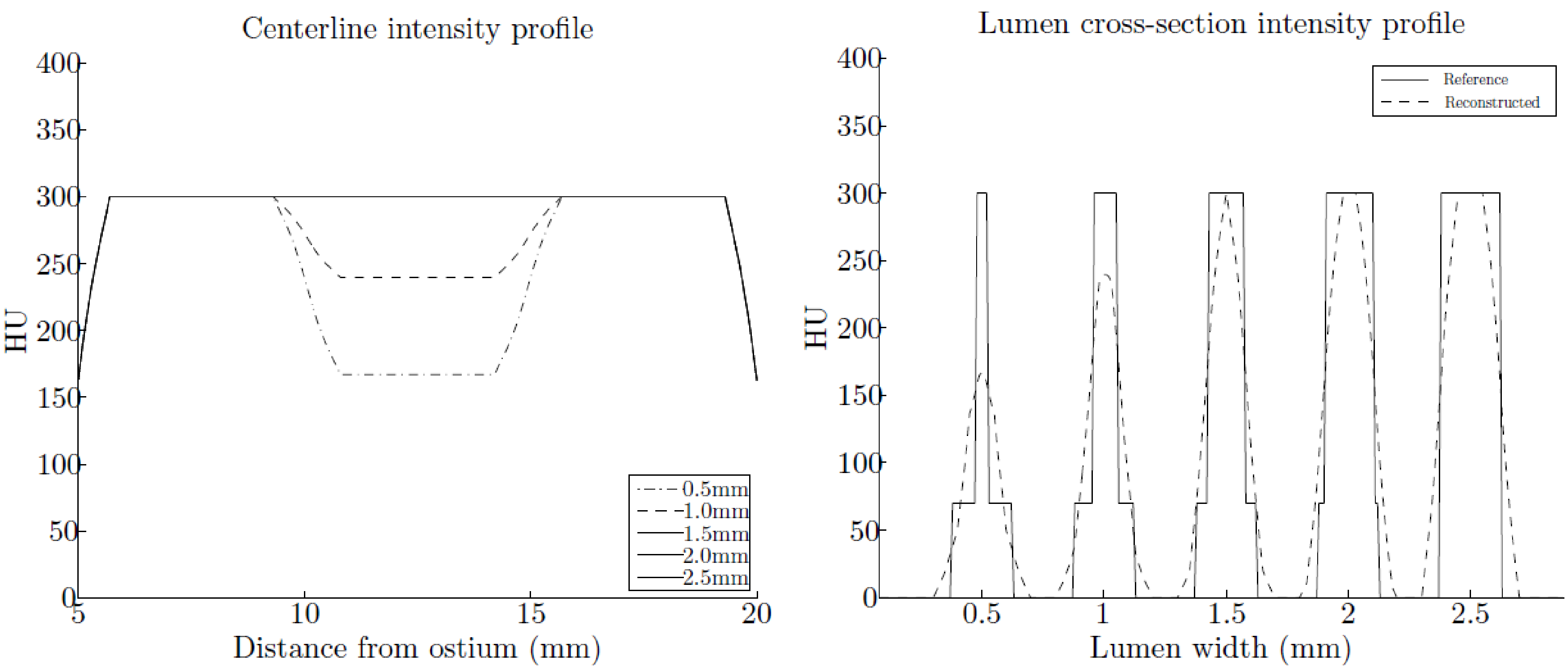
Partial volume effect on small-radius vessels



Small vessel diameters can be overestimated due to the overall system PSF[1] and **significantly impact flow simulation results**

1. Sato et all, MICCAI 2004

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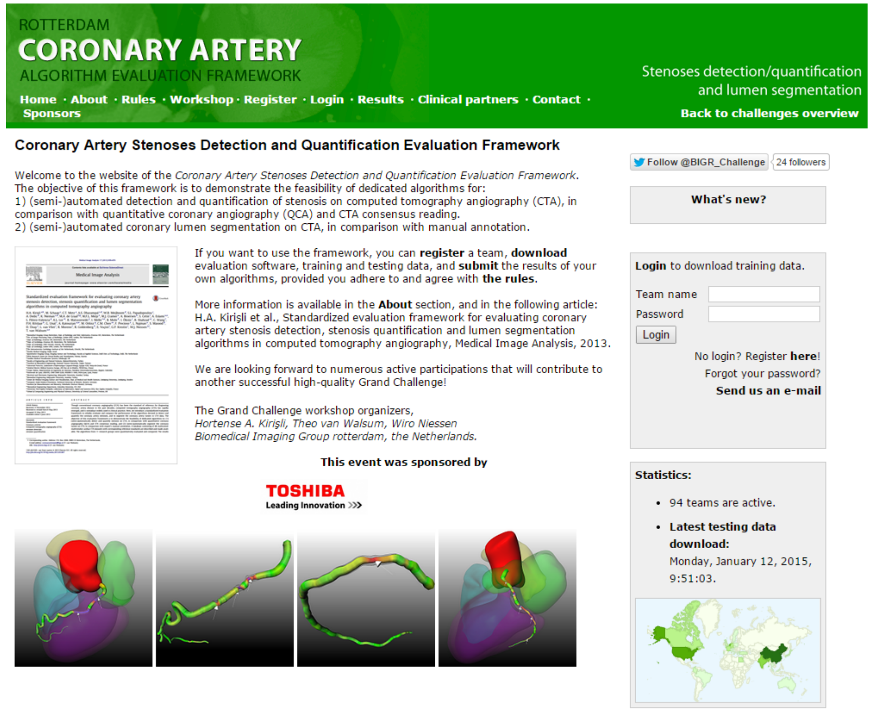
Previous works: MICCAI 2012 workshop



- **Evaluation was limited to anatomical agreement with manual segmentation without assessing impact on flow simulation accuracy**
- **Most methods did not consider the PV effect on small vessels diameters**

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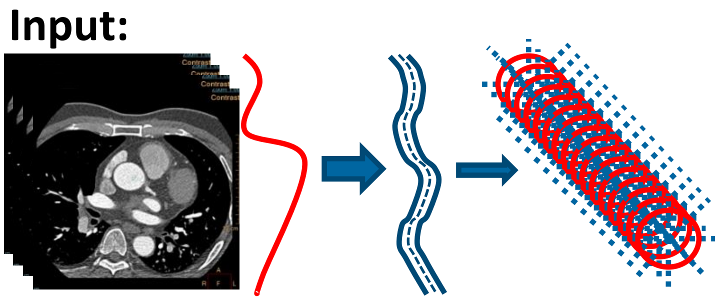
Our solution: Automatic coronary segmentation algorithm that accounts for the partial volume effect

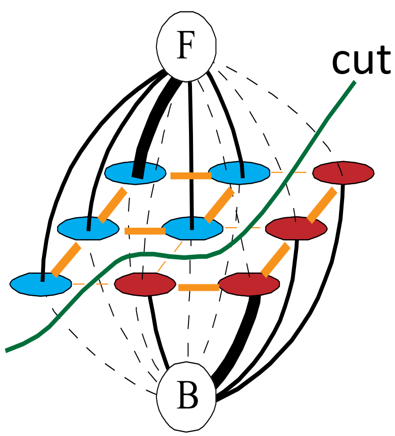


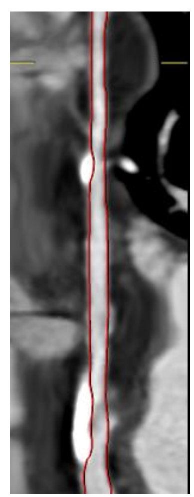
Machine-learning based likelihood + PV detection

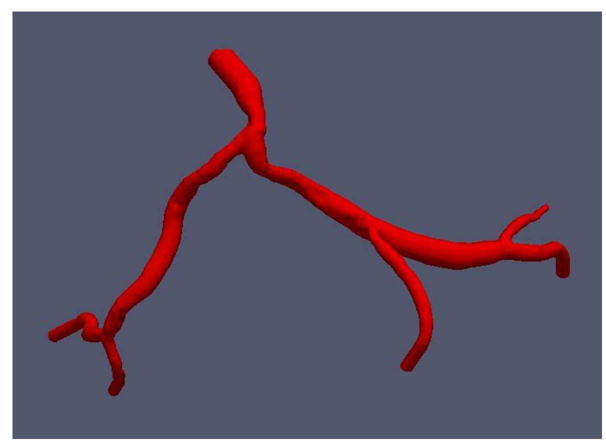
+

Regularization function

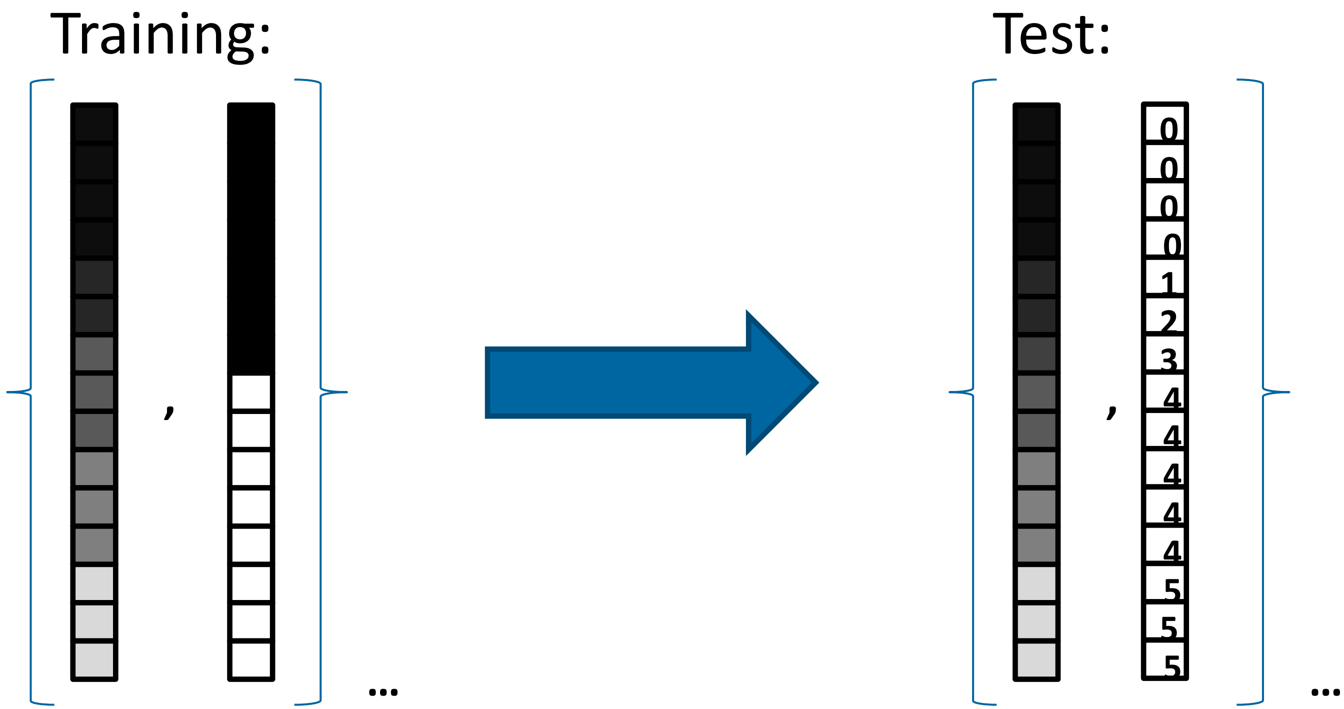
$$E(v) = \sum_{v} \phi(v) + \sum_{v_p, v_q \in \Omega} \psi(v_p, v_q)$$





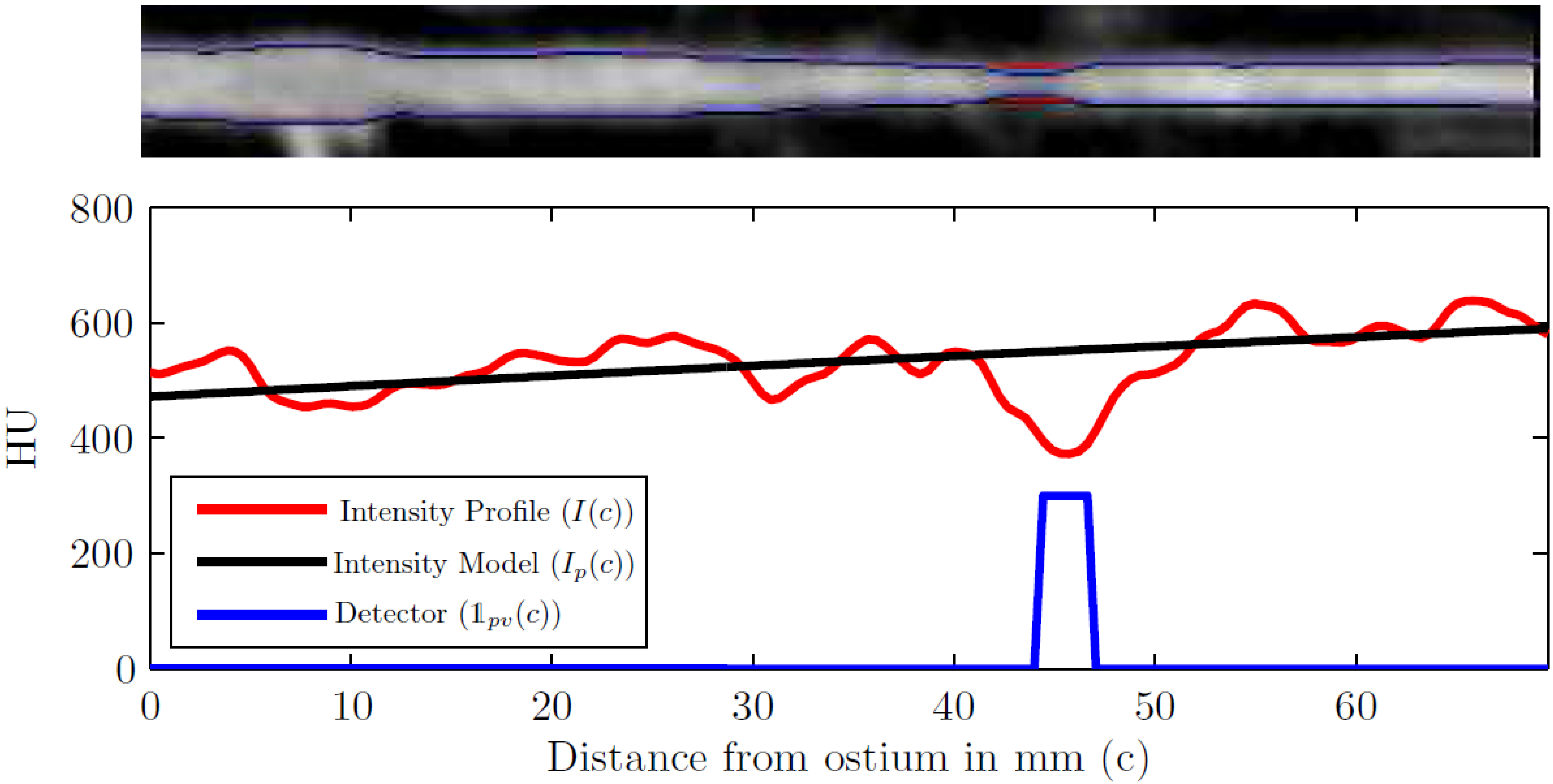


Approximate K nearest neighbor (L2) likelihood estimation



$$\mathrm{Pr}_d(x_p \in \mathrm{Lumen}) = \frac{\sum_{k=1}^{K} w(I(i^{x_p}, \theta^{x_p}, R), I'(i^k, \theta^k, R)) \cdot \delta(x_p, S(i^k, \theta^k, R))}{\sum_{k=1}^{K} w(I(i, \theta^{x_p}, R^{x_p}), I'(i^k, \theta^k, R))}$$

Partial Volume detection



Partial Volume detection: Algorithm steps

Input: Coronary centerline, Coronary centerline intensity profile

1. Robust intensity model fitting:

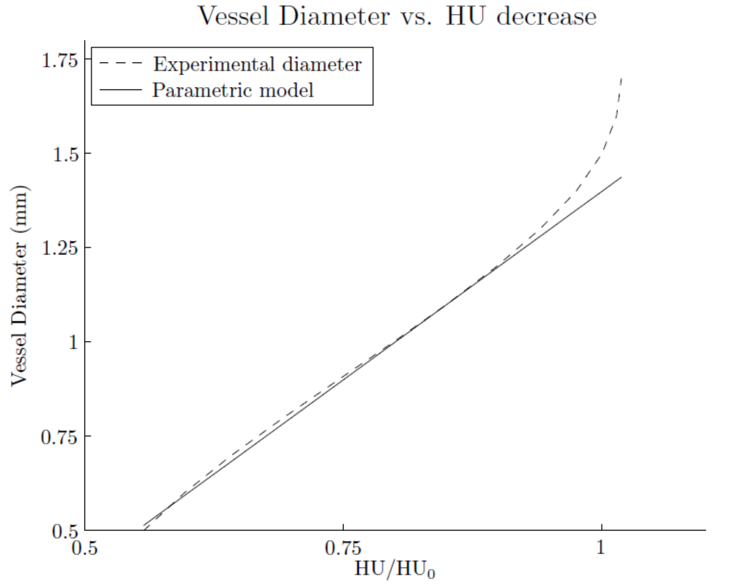
$$\widehat{I_p(C)} = \underset{I_p(C)}{\operatorname{argmin}} \sum_{c \in C} \Big(I(c) - I_p(c) \Big)^2$$

2. Detection of significant reduction in observed intensity compared to the model:

$$\mathbb{1}_{pv}(c) = \begin{cases} 1, & I(c) > (I_p(c) - 2\sigma_{I_c}) \\ 0, & I(c) \leq (I_p(c) - 2\sigma_{I_c}) \end{cases}$$

3. Underlying radius estimation based on pre-calculated model:

$$r(c) = 0.5\left(\alpha \left(1 - \frac{I(c)}{I_p(c)} \right) + \beta \right)$$



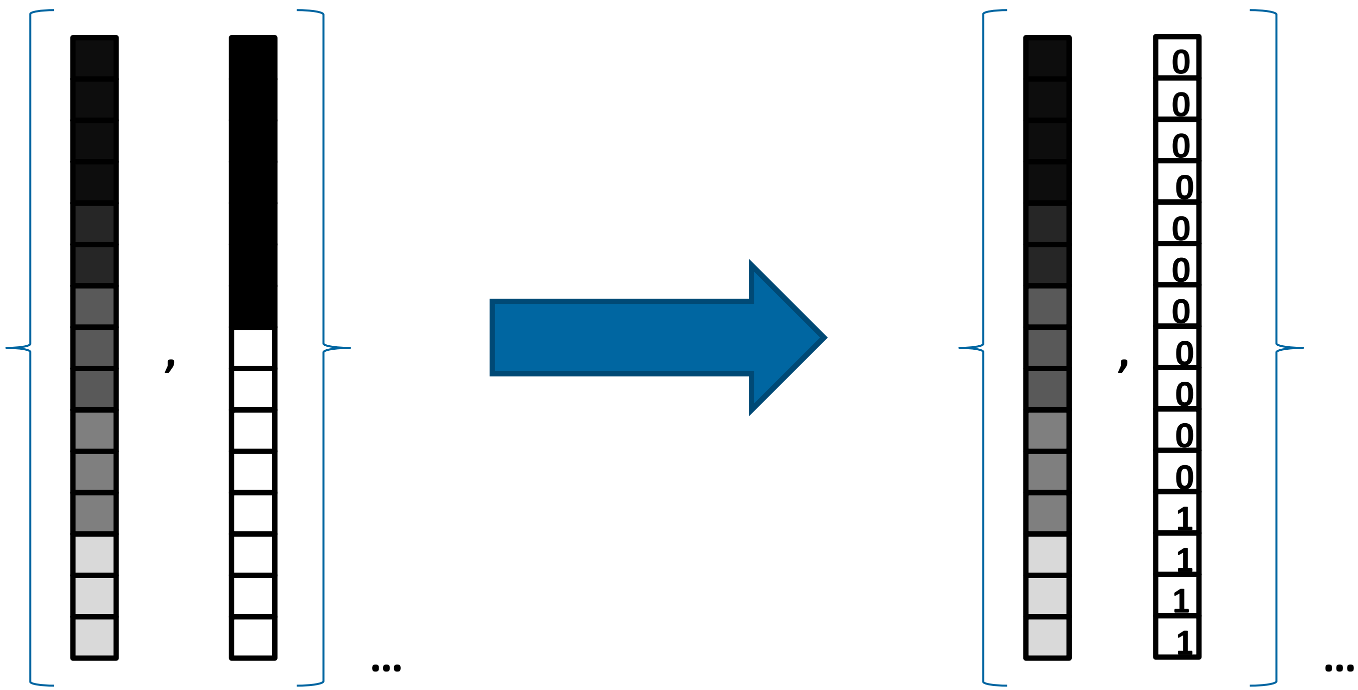
$$\Pr_{pv}(x_p \in \text{Lumen}) = \begin{cases} 0, & r^{x_p} \geq r' \\ 1, & r^{x_p} \leq r' \end{cases}$$

Output: Adjusted coronary radius at each centerline point after correction for PV

Applying PV radius correction on the likelihood map

Training:

Test:



$$\Pr(x_p \in \text{Lumen}) = \begin{cases} \Pr_d(x_p), & \mathbb{1}_{pv}(c(x_p)) = 0 \\ \Pr_{pv}(x_p), & \mathbb{1}_{pv}(c(x_p)) = 1 \end{cases}$$

Graph min-cut segmentation (Boykov et al, 2001)

- Binary separation of coronaries from the rest (background) formulated as a graph min-cut problem

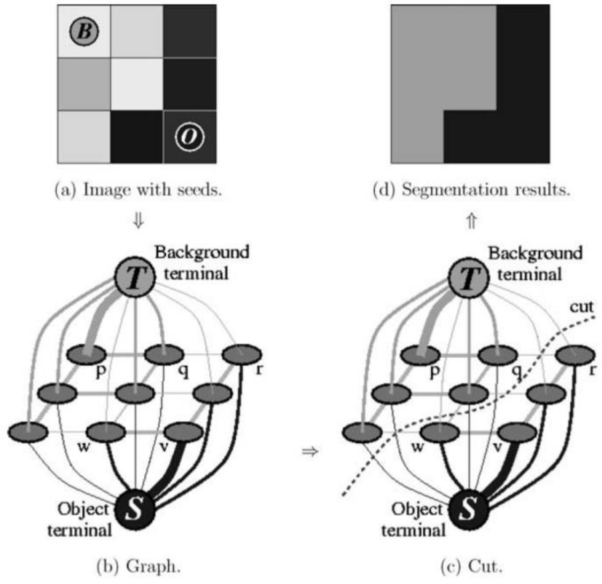
- Minimization of the following energy:

$$E(X) = \sum_{p \in P} \Psi_p(x_p) + \lambda \sum_{p,q \in E} \Psi_{p,q}(x_p, x_q)$$

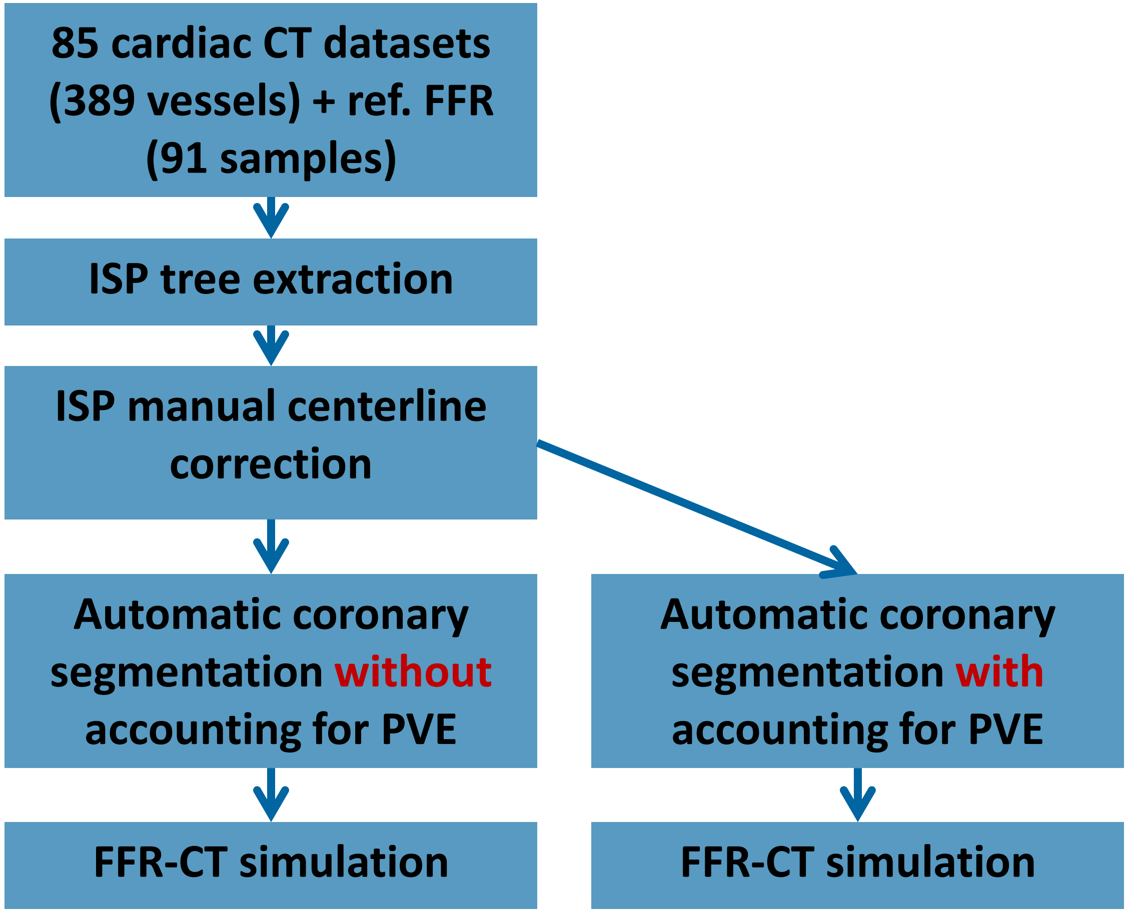
$$\Psi_p(x_p) = -\log \Pr(x_p \in \text{Lumen})$$

$$\Psi_{p,q}(x_p, x_q) = \exp\left(-\frac{(I(x_p) - I(x_q))^2}{\sigma_c(x_p)}\right) \cdot \exp(-d(x_p, x_q)^2)$$

- Globally optimal minimization for sub modular functions (edge weights ≥ 0)



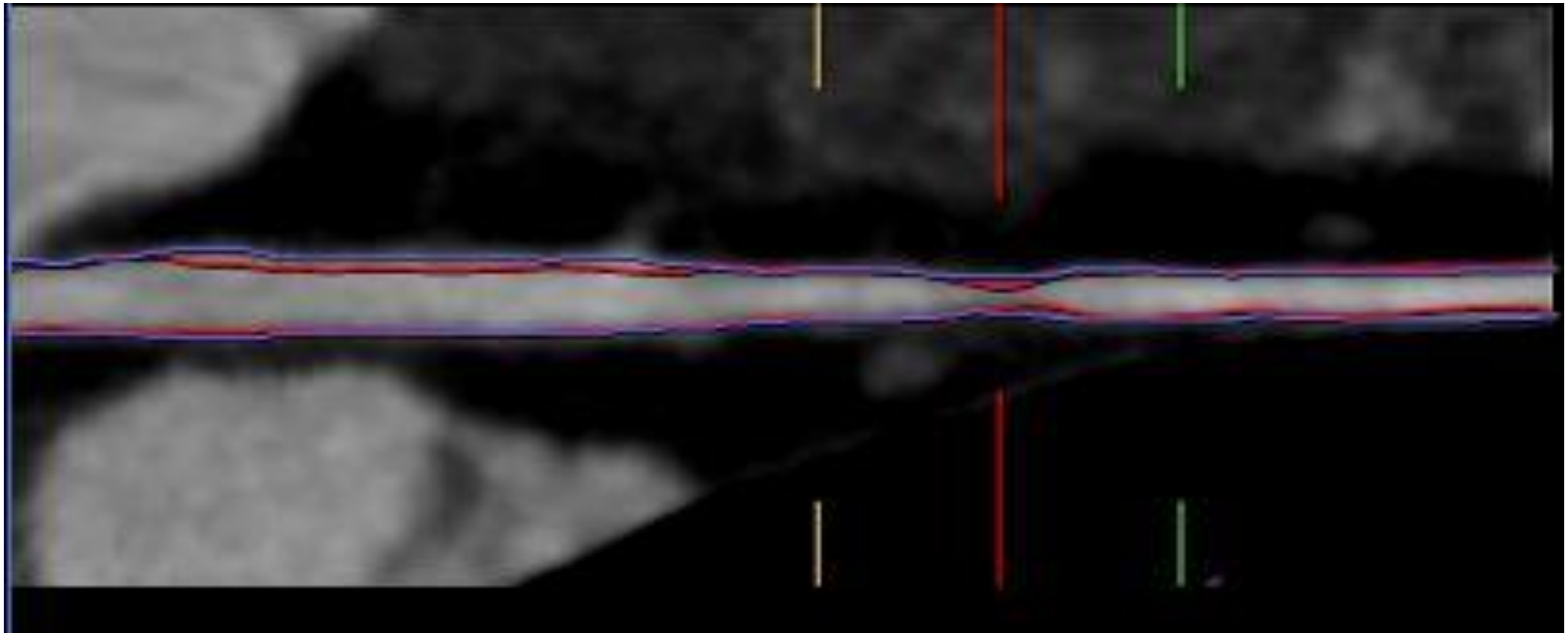
Experimental setup



Comparison: Flow simulation agreement with invasive FFR

Segmentation result: qualitative comparison

Without accounting for PVE



Blue – Automatic segmentation results without accounting for PVE
Red – manual expert segmentation that accounts for PVE

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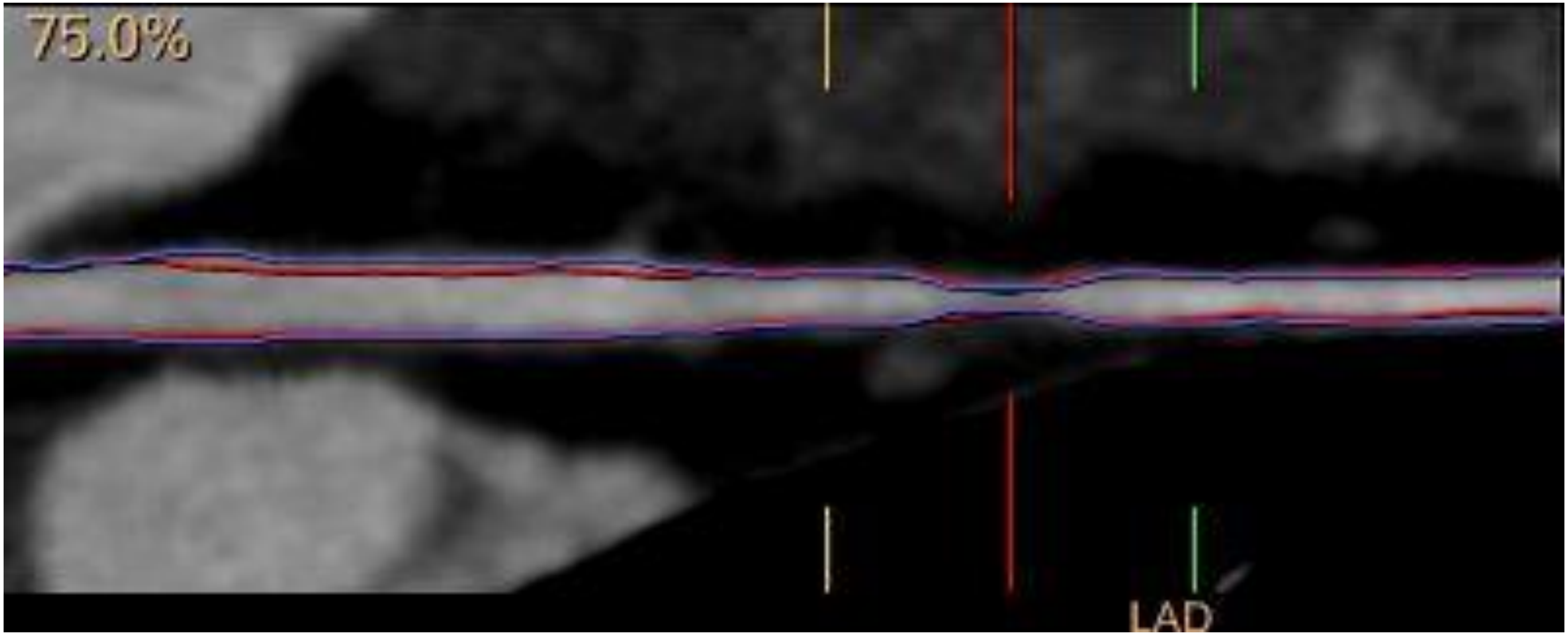
Segmentation result: qualitative comparison

With accounting for PVE



Blue – Automatic segmentation results with accounting for PVE
Red – manual expert segmentation that accounts for PVE

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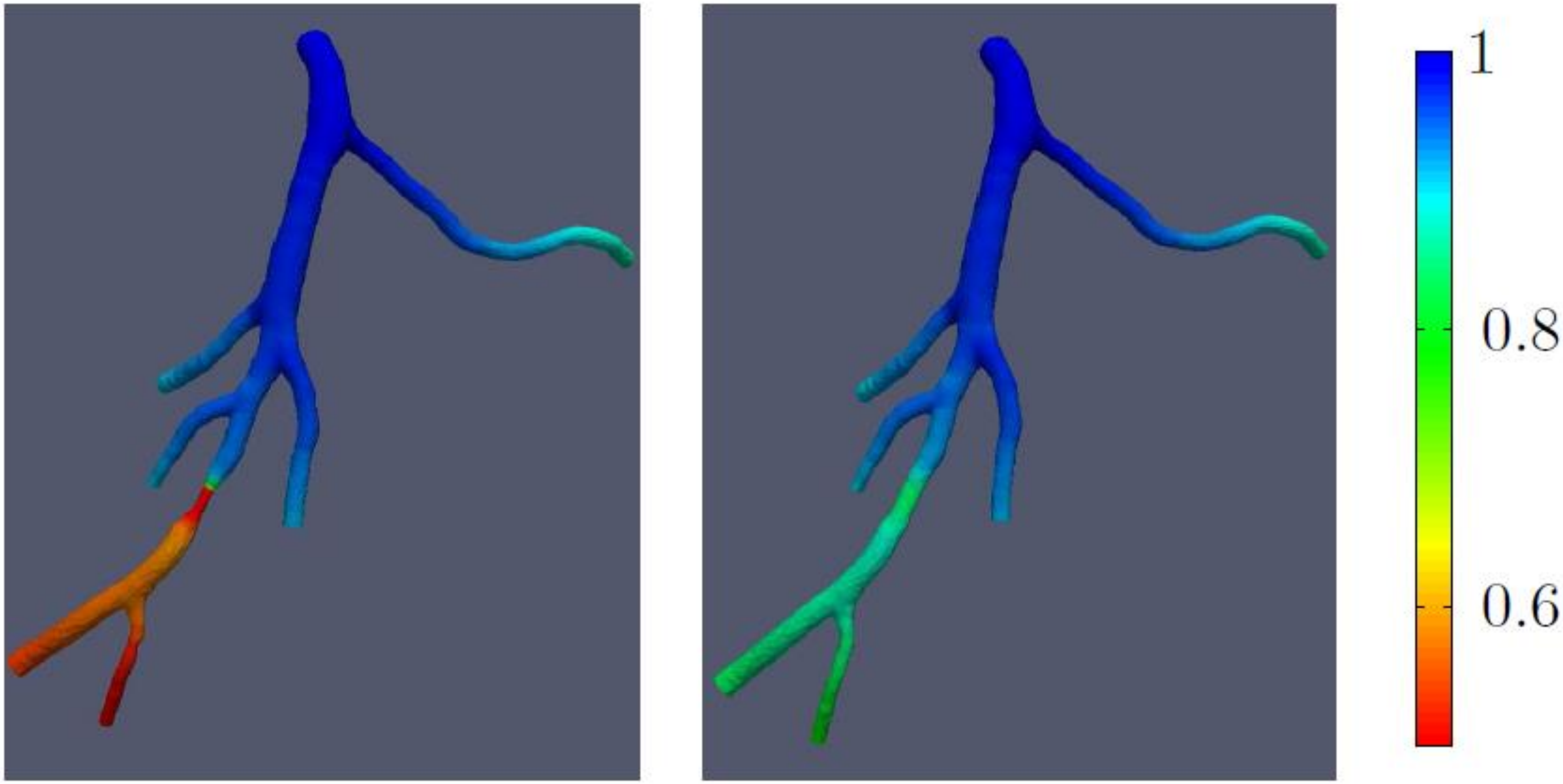
Experimental results: representative case



(a) With accounting for the PVE

(b) Without accounting for the PVE

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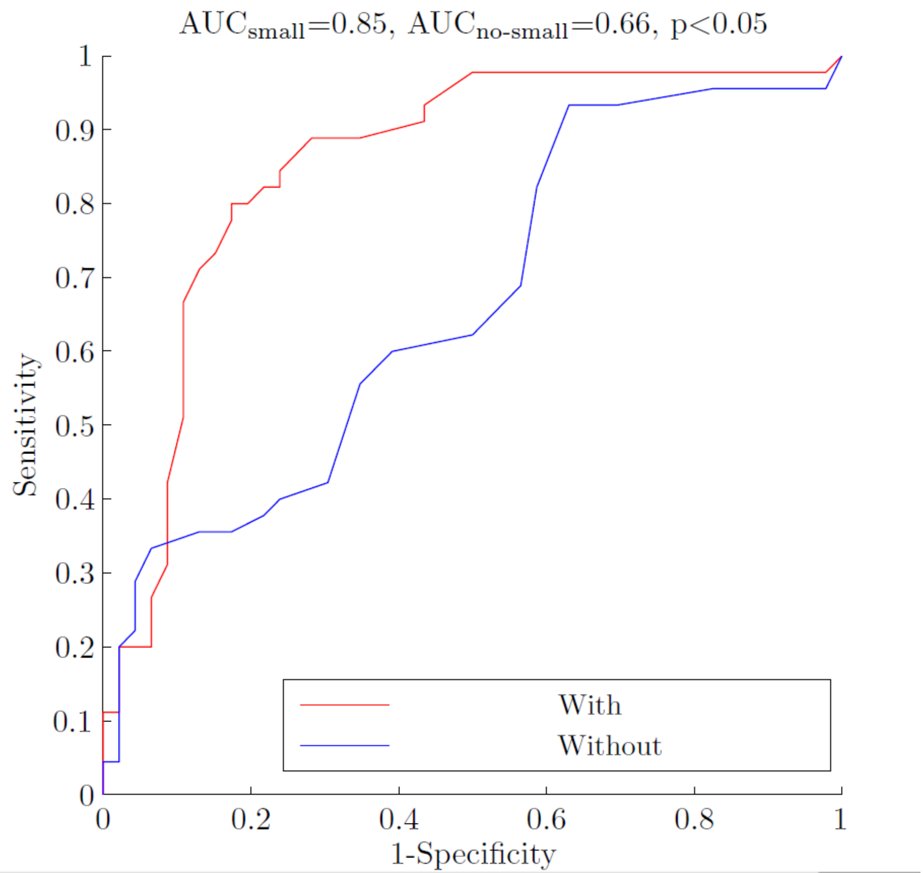
Experimental results: ROC analysis



Accounting for PVE significantly improved the detection performance by means of area under the ROC curve (AUC) by 29% (N=91, 0.85 vs. 0.66, p<0.05).

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Summary

- Functional assessment of coronary lesions based on CCTA and flow simulation requires accurate automatic lumen segmentation
- Partial volume effect may cause overestimation of small vessel diameter and reduce flow simulation accuracy
- Partial volume effect can be detected by analyzing the intensity profile along the vessel centerline
- New graph min-cut based algorithm for accurate coronary lumen segmentation that accounts for potential partial volume effects
- Accounting for partial volume in the automatic segmentation yield a substantial improvement in correlation between automatic estimation of FFR from CCTA and invasive FFR measurements

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