Vessel Enhancement With Multi-scale And Curvilinear Filters For Placenta Images

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Overview

- This project aims to develop an automated program that detects and enhances vessels in placenta images.
- A filtering process that is partly based on images' second-order characteristics is used to highlight image pixels from locally curvilinear structures while simultaneously decrease non-vessel noise.
- Enhancement results are reported in Matthews Correlation Coefficient (MCC) value as well as its area under the curve (AUC).
- The proposed enhancement procedure performs superior than an existing competitor's work (an neural network approach) as well as the method that utilizes multi-scale enhancement alone.

Why Study Placenta

- Recent medical research indicates that the placenta may be the crystal ball for the health of the baby.
- The placenta is the source of nutrition, oxygen, and blood for the developing fetus so any problem with the placenta may become a problem for the baby.
- An analysis of the placenta may help to predict risks for certain diseases that develop in the womb such as diabetes, autism, and heart disease.
- In particular, the structure of the blood vessel network as well as the shape of the human placenta may contain important medical clues.

Question: Which one of following placentas is associated with a healthy baby?

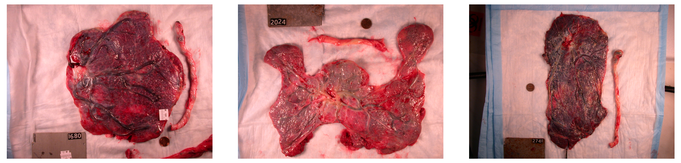
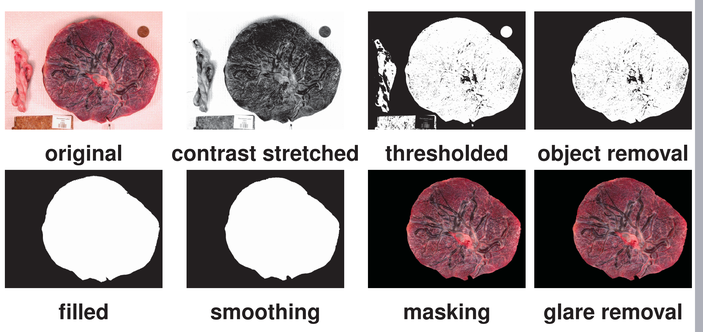


Figure: Sample digital placenta images in the UNC data set provided by Placental Analytics.

Preprocessing

Preprocessing in this context entails a preparation of useable images by removing irrelevant objects, reducing glare, and enhancing contrast to arrive at images that are ready for vessel extraction.



Proposed Vessel Enhancement Process

Step 1: The Multi-scale Filter

- Let $I(x, y)$ denote a 2D digital (grayscale) image and G a **Gaussian** filter function, its (continuous version) **Hessian** matrix is given by
$$H = G \star \begin{pmatrix} I_{xx} & I_{xy} \\ I_{xy} & I_{yy} \end{pmatrix}.$$
- Let $\mathbf{u}_1$ and $\mathbf{u}_2$ denote eigenvectors of H corresponding to **eigenvalues** λ_1 and λ_2 satisfying $|\lambda_1| < |\lambda_2|$, respectively.
- These eigenvalues can then be used to define two *vesselness* measures suited for medical images:
$$\text{(anisotropy)} \quad A = \frac{|\lambda_1|}{|\lambda_2|}, \quad \text{and}$$
$$\text{(structureness)} \quad S = \sqrt{\lambda_1^2 + \lambda_2^2}.$$
- With these two measures, the probability of a pixel being a vessel is given by
$$F\{\cdot\} = \begin{cases} 0 & \text{if } \lambda_2 < 0, \\ \exp\left(\frac{-A^2}{2\beta^2}\right)\left(1 - \exp\left(\frac{-S^2}{2c^2}\right)\right) & \text{otherwise} \end{cases}$$
where β and c are scaling parameters that control the sensitivity of the vesselness measures.
- The use of this multi-scale filter alone is not satisfying due to the nature of the placenta images.

Step 2: Curvilinear Filter Matching

1. Enlarge each image with a bi-cubic interpolation by a factor of s to obtain I_s.
2. For each image pixel (X, Y), determine whether it is a vessel pixel using a binary response function
$$B(X, Y) = \begin{cases} 1 & \text{if} \quad F\{I_s(X, Y)\} > \lambda \quad (\lambda = 0 \quad \text{in our experiments}) \\ 0 & \text{otherwise} \end{cases}$$
3. A curvilinear filter function is proposed here
$$\Psi(x, y) = \begin{cases} \frac{1-w^2x^2}{4-w^2x^2}\, e^{-\frac{1}{2}\left(\frac{3}{4-w^2x^2} + \ell^2 y^2\right)} & \text{if} \quad |x| \le 2w \\ 0 & \text{if} \quad |x| > 2w \end{cases}$$
to highlight locally linear structure by controlling the width (w) and length (ℓ) parameters, while penalizing neighborhood pixels that present non-cohesive structure.

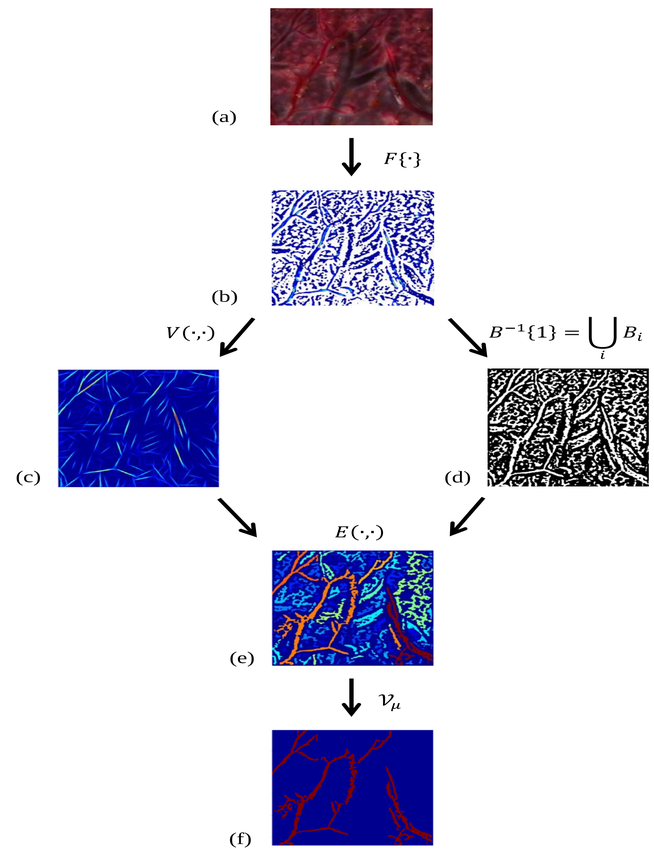
4. To account for direction information, specify a collection of the curvilinear templates $W_k(x, y) = \Psi \circ T_k(x, y)$, where
$$T_k(x, y) = \begin{bmatrix} \cos\theta_k & -\sin\theta_k \\ \sin\theta_k & \cos\theta_k \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$
and $\theta_k = \frac{k\pi}{n}$ for some fixed n.
5. With this, a *curvilinear filter (CLF) response* is computed by considering $V_k(x, y) := (W_k * B)(x, y)$ for various k, where $*$ denotes the usual convolution.
6. Finally, from the collections of CLF responses, a point (x, y) is assigned the maximum CLF response
$$V(x, y) = \max_{1 \le k \le n} V_k(x, y),$$
which represents the amount of curvilinear structure the pixel possesses.

Step 3: Enhancement

The curvilinear filter identifies the linear regions from the multiscale filtered results. To take advantage of both methods, we propose the following enhancement procedure.

1. The set of pixels identified as potential vessels by the multiscale filter, $B^{-1}\{1\}$, is the union of distinct connected components $\{B_i\}$. That is,
$$B^{-1}\{1\} = \bigcup_i B_i.$$
2. For each $(x_0, y_0) \in B_i$, let $E(x_0, y_0) = \max_{(x,y) \in B_i} \{V(x, y), 0\}$ be the enhanced response.
3. At the end of this enhancement process, there will be a collection of points that are identified as vessels:
$$\mathcal{V}_\mu = \{(x, y) \mid E(x, y) > \mu\}.$$

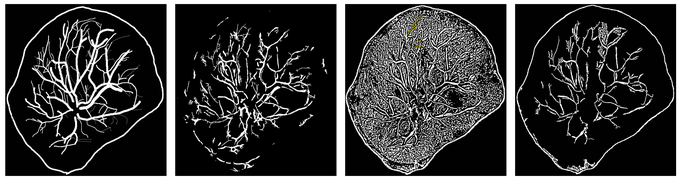
Visualization of the Method



A Sample Result

The Matthew's Correlation Coefficient (MCC) metric is used to measure how related the identification of the vessels are to the actual vessel locations:

$$\text{MCC}(x, y) = \frac{\text{TP} \times \text{TN} - \text{FP} \times \text{FN}}{\sqrt{(\text{TP} + \text{FN})(\text{TP} + \text{FP})(\text{TN} + \text{FP})(\text{TN} + \text{FN})}}$$



(a) (b) (c) (d)

Figure: (a) Hand tracing. (b) Competitor's results. (c) Multi-scale with a threshold of 0. (d) Proposed enhancement with $s = 3$, $\sigma = 5$, $w = 14$, $\ell = 36$, $k = \{1, \ldots, 12\}$.

Method	MCC value	AUC of MCC
Competitor's (neural network)	0.345	0.22
Multi-scale only	0.2552	0.1216
Proposed enhancement	**0.3539**	**0.2500**

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