Abstract

Classification of tortuosity of corneal subbasal nerves by in vivo confocal microscopy (IVCM) images is complicated by the presence of variable numbers of nerve fibres with different tortuosity levels. Instead of designing a function combining manually selected features into a single coefficient, as done by other groups, we propose a supervised approach which selects automatically the most relevant combination of shape features from a pre-defined dictionary.

To the best of our knowledge, we are the first group to experimentally their relevance in tortuosity modelling. Our results, obtained with a set of 100 images and 20 fold cross-validation, suggest that multinomial logistic ordinal regression, trained on consensus ground truth from 3 experts, yields an accuracy indistinguishable, overall, from that of experts when compared against each other.

Main Contributions

- Multiscale analysis of nerve fibre tortuosity features;
- New, highly accurate numerical curvature estimation applied to corneal nerve fibres
- Automatic identification of most relevant set of scale-space features
- Supervised approach for combining features as opposed to hand-crafted tortuosity definitions
- Dataset:
  - 100 images, 3 independent annotators
  - noisy labels (i.e. modest agreement among annotators)
  - 4 levels of tortuosity to be assessed

Experiments: Classifying Corneal Nerve Images

- Modest inter-observer agreement (< 50%), so we use Consensus Ground Truth (CGT - 90 images).

Association with CGT

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>MLOR</th>
<th>OSVM</th>
</tr>
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<tbody>
<tr>
<td>Acc</td>
<td>84.44%</td>
<td>80.56%</td>
</tr>
<tr>
<td>Se</td>
<td>69.77%</td>
<td>61.94%</td>
</tr>
<tr>
<td>Sp</td>
<td>89.50%</td>
<td>86.86%</td>
</tr>
<tr>
<td>Ppv</td>
<td>69.75%</td>
<td>62.61%</td>
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<tr>
<td>Npv</td>
<td>89.48%</td>
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<tr>
<td>MNE</td>
<td>0.3444</td>
<td>0.4222</td>
</tr>
<tr>
<td>MAE</td>
<td>0.3222</td>
<td>0.4000</td>
</tr>
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</table>

Association with individual GT (Accuracy)

<table>
<thead>
<tr>
<th></th>
<th>A.</th>
<th>PH</th>
<th>SA</th>
<th>MLOR</th>
</tr>
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<tbody>
<tr>
<td>AK</td>
<td>100%</td>
<td>76.67%</td>
<td>75%</td>
<td>88.89%</td>
</tr>
<tr>
<td>PH</td>
<td>76.67%</td>
<td>100%</td>
<td>73.89%</td>
<td>67.67%</td>
</tr>
<tr>
<td>SA</td>
<td>75%</td>
<td>73.89%</td>
<td>100%</td>
<td>77.22%</td>
</tr>
</tbody>
</table>

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Proposed Approach

1. At each pixel, apply local ellipse fitting and line fitting using the smallest window size in a pre-defined range, \( R = [w_l, w_u] \);
2. Choose the best fitting function (ellipse-arc or line) based on the sum of squared errors;
3. If ellipse-arc is the best fitting function, compute the curvature using analytical derivatives on the estimated ellipse;
4. Repeat 1–3. for all windows in \( R \);
5. Select the maximum estimated curvature over all windows after median filtering to eliminate small, spurious peaks.

A Multiple-Window Approach for Digital Curvature Estimation

- Scale seems to play a role and a multi-scale approach is effective;
- Automatic feature selection, instead of intuitively choosing them, gives promising results;
- Supervised approach instead of single formula for tortuosity estimation;
- New approach for digital curvature estimation applied to corneal nerve fibres;
- First to propose an automatic method capable of predicting more than 3 tortuosity levels.

Conclusions

1. At each pixel, apply local ellipse fitting and line fitting using the smallest window size in a pre-defined range, \( R = [w_l, w_u] \);
2. Choose the best fitting function (ellipse-arc or line) based on the sum of squared errors;
3. If ellipse-arc is the best fitting function, compute the curvature using analytical derivatives on the estimated ellipse;
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Examples of predictions on the “tortuosity plane”

Each image is represented as a point on the plane generated by \( K_{mean}(2) \) and \( K_{mean}(5) \). Different markers are used for images with (actual) different tortuosity levels (CGT). Colour is a visual measure of predictive confidence: high confidence (red), low confidence (blue). Black lines are predicted decision boundaries.