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Algorithms for digital image processing in diabetic retinopathy

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ABSTRACT

This work examined recent literature on digital image processing in the field of diabetic retinopathy. Algorithms were categorized into 5 steps (preprocessing; localization and segmentation of the optic disk; segmentation of the retinal vasculature; localization of the macula and fovea; localization and segmentation of retinopathy). The variety of outcome measures, use of a gold standard or ground truth, data sample sizes and the use of image databases is discussed. It is intended that our classification of algorithms into a small number of categories, definition of terms and discussion of evolving techniques will provide guidance to algorithm designers for diabetic retinopathy.

1. Introduction

Over the last decade, high resolution color digital photography has been recognized as an acceptable modality for documenting retinal appearance. Images are easily captured using a conventional digital camera back, attached to a retinal camera body designed to compensate for the optics of the eye. The digital format provides a permanent, high quality record of the appearance of the retina at any point in time. Electronic storage, retrieval and transmission are possible without loss of image quality.

One well recognized application for retinal digital imaging is within screening programs for diabetic retinopathy (DR). This disease is the commonest cause of blindness in people of working age, has an effective treatment available to prevent vision loss but is asymptomatic until late in the disease process. The UK National Screening Committee currently recommends annual screening for all diabetic patients aged 12 years and over, using digital retinal photography (www.nscretinopathy.org.uk). Images may be captured at a venue convenient to the patient's home or work and data then transferred to a central location where they are read and interpreted by trained graders. Quality assurance must be an integral component of any screening programme, and as in breast screening programs, a high proportion of all images should be double read.

Population growth, an aging population, physical inactivity and increasing levels of obesity are contributing factors to the increase in the prevalence of diabetes. The global prevalence of diabetes is expected to rise from 2.8% in 2000 to 4.4% of the global population by 2030 [1]. In the UK the number of diabetic people is approximately 2.3 million (www.diabetes.org.uk). If all diabetic people are to undergo regular screening within a quality assured framework, the workload is going to be substantial.

Grading retinal images for the presence of diabetic retinopathy is largely a pattern recognition task. The typical features of diabetic retinopathy are microaneurysms, small intra retinal dot hemorrhages, larger blot hemorrhages, all of which are red lesions, and whitish lesions for example lipid exudates, and cotton wool spots which are nerve fiber layer microinfarcts. Graders are taught to recognize these lesions against the background appearance of the 'normal retina'. With an increasing diabetic population and the need for quality assurance pathways, it is not surprising that considerable effort has been spent over the past 10–15 years on investigating whether these lesions could be detected by computer aided pattern recognition algorithms.

The process of detecting multiple patterns and their relationship within a retinal image is made up of a series of operations or steps, with low-level image processing operations providing a basis for higher level analysis. Digital retinal images are usually processed in an algorithmic sequence, with the output of one stage forming the input to the next. For example, a typical sequence may consist of one or more preprocessing procedures followed by image segmentation, feature extraction and classification stages. Preprocessing may be used to normalize image brightness, correct for image nonuniformity, reduce noise or reduce image artifacts. Segmentation decomposes an image into its constituent regions or objects, for example retinal blood vessels, optic nerve head or pathological lesions. Feature extraction typically computes quantitative infor-

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Table 1
List of references of the papers which addressed steps A–E either in part or in full.

A. Preprocessing
Badea et al. [78]; Cree et al. [25]; Ege et al. [37]; Foracchia et al. [6]; Gagnon et al. [96]; Goatman et al. [23]; Goh et al. [103]; Hipwell et al. [68]; Narasimha-Iyer et al. [126,64]; Osareh et al. [24]; Raman et al. [139]; Sinthanayothin et al [71,145]; Usher et al. [27]; Walter and Klein [152]; Yang et al. [157]; Zhang and Chutatape [158]

B. Localization and segmentation of the optic disk
Abdel-Razik et al. [76]; Chutatape and Li [86]; Eswaran et al. [92]; Fleming et al. [94]; Foracchia et al. [8]; Gagnon et al. [96]; Goh et al. [103]; Hajer et al. [106]; Hoover and Goldbaum [43,3]; Hwee et al. [112]; Kochner et al. [36]; Lalonde et al. [41]; Lee et al. [118]; Li and Chutatape [120,121,63,39]; Lowell et al. [28]; Mendels et al. [49]; Narasimha-Iyer et al. [126,64]; Niemeijer et al. [130], Noronha et al. [132]; Osareh et al. [133]; Sanchez et al. [40]; Saradhi et al. [142]; Sekhar et al. [144]; Simandjuntak et al. [146]; Sinthanayothin et al. [21,71,145]; Tobin et al. [65]; Usher et al. [27]; Walter and Klein [46,13,152,153]

C. Segmentation of the retinal vasculature
Abdel-Razik et al. [76]; Abdurrazaq et al. [77]; Can et al. [79,80,81]; Chanwimaluang et al. [82,83]; Chapman et al. [84]; Chutatape et al. [85,86]; Cornforth et al. [87]; Dua et al. [89]; Estabridis et al. [91]; Fang et al. [93]; Fleming et al. [94]; Gagnon et al. [96]; Gang et al. [97]; Gao et al. [99,100,101]; Goh et al. [103]; Grisan et al. [104]; Hayashi et al. [108]; Hong et al. [109,110]; Hoover et al. [44]; Hsu et al. [111]; Hwee et al. [112]; Iqbal et al. [113]; Jiang et al. [114]; Kochner et al. [36]; Lalonde et al. [30,117]; Leandro et al. [18]; Lee et al. [119]; Li and Chutatape [120,122]; Lowell et al. [53]; Mahadevan et al. [124]; Martinez-Perez et al. [125]; Narasimha-Iyer et al. [126,64]; Niemeijer et al. [131,129]; Noronha et al. [132]; Pedersen et al. [135]; Pham et al. [136]; Raman et al. [139]; Sanchez et al. [40]; Simandjuntak et al. [146]; Sinthanayothin et al. [21,71,145]; Staal et al. [147]; Tan et al. [148]; Truitt et al. [149]; Tsai et al. [150]; Usher et al. [27]; Walter and Klein [46,13,152]; Yang et al. [57]

D. Localization of the macula and fovea
Chutatape and Li [86]; Estabridis et al. [90]; Fleming et al. [94]; Gagnon et al. [96]; Li et al. [63,39]; Narasimha-Iyer et al. [126,64]; Niemeijer et al. [129]; Noronha et al. [132]; Simandjuntak et al. [146], Sinthanayothin et al. [21,71,145]; Tobin et al. [65]

E. Segmentation of retinopathy
Badea et al. [78]; Cree et al. [25]; David et al. [88]; Ege et al. [37]; Estabridis et al. [90]; Eswaran et al. [92]; Fleming et al. [94]; Fleming et al. [95]; Gang et al. [98]; Garcia et al. [102]; Goh et al. [103]; Grisan et al. [105]; Hansen et al. [107]; Hipwell et al. [68]; Hsu et al. [111]; Kahai et al. [115,116]; Kochner et al. [36]; Larsen et al. [73]; Lee et al. [72], Li et al. [120,63,39]; Luo et al. [123]; Narasimha-Iyer et al. [126,64]; Nayak et al. [127]; Niemeijer et al. [128,129]; Noronha et al. [132]; Osareh et al. [24]; Pallawala et al. [134]; Quellec et al. [137,138]; Raman et al. [139], Sagar et al. [140]; Sanchez et al. [40,141]; Satyarthi et al. [143]; Sinthanayothin et al. [71,145]; Truitt et al. [149]; Usher et al. [27]; Vallabha et al. [151]; Walter and Klein [13,152,153,154]; Wang et al. [14]; Xiaohui et al. [155,156]; Yang et al. [57,157]; Zhang and Chutatape [158]

mation from the segmented objects. The extracted features can be used to classify objects according to predetermined criteria such as size, morphology and color.

The objectives of this paper are

(1) to review the relevant literature over a 10 year period in the field of digital image processing in DR;
(2) to provide researchers with a detailed resource of the main algorithms employed;
(3) to categorize the literature into a series of operations or steps;
(4) to identify potential areas for improving research design and reporting.

The paper is organized as follows: Section 2 describes the methodology used for the literature review. Section 3 gives the results of the review. Section 4 provides a detailed survey of the common computational steps for detecting retinal features. The image processing operations for detecting the optic nerve head, retinal vasculature, fovea, macula and retinopathy are described. We conclude in Section 2 by discussing recent trends and directions for future work.

2. Literature survey methodology

In their 2003 report for NHS Health Technology Assessment (HTA) [2] Sharp and co-authors included in their objectives, a systematic literature review of digital imaging technology as applied to diabetic retinopathy. This review was completed in 1998. The authors stated that their original intent was to provide a quantitative analysis of different digital imaging techniques. They found that this was not possible owing to the early stage of evolution of digital technology in this field.

The work reported in this paper analyses and categorizes the literature on the use of digital imaging techniques in diabetic retinopathy during the period 1998–2008. Further literature is included in the text to illustrate the development of image processing techniques and algorithms in this field. However this supporting literature was not included in the analysis reported in Section 3. A survey methodology was developed which included the search strategy, data extraction from the literature and analysis of findings. The following bibliographic databases were searched systematically: PubMed (National Library of Medicine), MEDLINE, EMBASE (Elsevier Science Publishers), Cochrane Library (Wiley), EI Compendex Plus (Elsevier Science Publishers); National Research Register (NRR), IEEExplore Digital Library (IEEE).

The studies included in this survey examined the use of novel computer algorithms to detect normal and pathological retinal features within the context of diabetic retinopathy. Secondary source articles describing the algorithms applied were identified from the reference lists of the reviewed articles and, although some were outside the date range, they were included for completeness. Analysis of the literature was carried out as follows: papers were categorized according to the image processing step(s) addressed and algorithms used; an analysis of reporting and/or evaluation methodologies was performed using the following five factors: reproducible description of the methodology; sample size if quoted; the use of a defined standard; objective result presented in numerical terms; sensitivity and specificity data reported. The literature was reviewed and a detailed overview of the image processing steps is presented in Section 4.

3. Literature survey results

One hundred and twenty seven articles were identified which met the criteria for inclusion. Where possible the main focus of each paper was identified, in terms of which step in the processing sequence was addressed. Five primary steps were defined: preprocessing (A); localization and segmentation of the optic disk (B); segmentation of the retinal vasculature (C); localization of the macula and fovea (D); and localization and segmentation of retinopathy (E). Table 1 lists references of the papers which addressed steps A–E either in part or in full. Full paper details are provided in the reference list.

Fig. 1 shows the number of papers which addressed each step in the processing sequence (A–E). Segmentation of the retinal vasculature (Step C) was a major area of focus within the literature, with 62 articles presenting techniques used for this step in the process. In contrast, less work was reported on localization of the macula and fovea (Step D).