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Preface

The tongue, as the primary organ of gustation, conveys abundant valuable information about the health status of the human body, i.e., disorders or even pathological changes of internal organs can be reflected by the human tongue and observed by medical practitioners. Tongue diagnosis (TD), a noninvasive diagnostic method using inspection of the appearance of human tongue, has played an indispensable role in Traditional Chinese Medicine (TCM) for over 2,000 years. In recent years, for the purpose of academic research, significant information technologies, including digitalized data acquisition, image processing, and pattern recognition have been widely used in tongue diagnosis to improve its diagnostic validity and accuracy. Computerized tongue diagnosis (CTD), as a result, has become a fundamental part of the revolution that has taken place at an ever-increasing pace over the past decade in TCM. The growing importance and rapid progress in CTD has brought about an independent and burgeoning branch in the TCM research field, and also resulted in urgent and extensive requirements for tongue image analytical techniques.

By its very nature, tongue image analysis is cross-disciplinary in several aspects. First, before a tongue image can be analyzed, it is imperative that the basic principles of TD should be mastered. For instance, we should know what kinds of visible information are crucial for the visual inspection process of TD. This mainly includes several aspects in the TCM and computer vision (CV) research fields. Next, in order to get useful data, a special acquisition system should be carefully designed to guarantee that all the information is included in the signal acquired by the imaging sensor. This incorporates the interaction of optics of matter to the geometry and radiometry of imaging and industrial design. Finally, after being captured and converted into digital form, the tongue image should be processed, analyzed, and classified by the computer. In this chain of processes, many areas from computer science and mathematics are involved, e.g., computer architecture, algebra, analysis, statistics, algorithm theory, graph theory, system theory, and numerical mathematics, all of which have a partial or strong association with tongue image analysis.

Today, the field of modern tongue diagnosis is becoming more technical. Although practitioners need to understand the basic theory and practice of computer science such as image processing and pattern recognition, they also need guidance on how to actually address thorny problems such as automatic segmentation, color distortion, and robust classification of tongue images which are very helpful to the practicing CTD scientist.

It is the purpose of this book, as briefly and concisely as possible, to give the reader a straightforward and intuitive introduction to basic and advanced techniques in tongue image processing and analysis and their typical applications in CTD systems. It features the most current research findings in all aspects of tongue image acquisition, preprocessing, classification, and diagnostic support methodologies, from theoretical and algorithmic problems to prototype design and development of CTD systems.

In the first two chapters, the book begins with a very high-level description of CTD on a need-to-know basis which includes an overview of CTD systems and Traditional Chinese Medicine (TCM) as the context and background knowledge of tongue image analysis. From Chaps. 3 to 13, the principal part of the book then provides useful algorithms as well as their implementation methods of tongue image analysis. The most notable extensions, at a know-how level, include detailed discussions on segmentation, chromatic correction, and classification which are arranged in systematic order as follows.

The first preprocessing step of tongue image processing and CTD, automated tongue image segmentation is difficult due to two special factors. First, there are many pathological details on the surface of the tongue, which have a large influence on edge extraction. Second, the shapes of tongue bodies captured from various persons are quite different. So far, there is no single solution that can address all the problems in automated tongue image segmentation. From Chaps. 3 to 7, the book presents five different segmentation approaches to solve domain problems based on different kinds of tongue images. These methods are robust to noise caused by a variety of shapes and irrelevant information from non-tongue parts such as lips, beard, and facial skin. After segmenting the tongue area from its surroundings, a study on tongue shape analysis by using the tongue contour and its geometric features is then introduced in Chap. 8 as the end of Part II.

Part III makes a sound exposition of the quantitative classification of tongue images beginning with the correction of the color feature in tongue image. Color inconsistency is the second problem CTD scientists have to face before analyzing the tongue image. Since the colors of the tongue image produced by digital cameras are usually device-dependent, this is a serious problem in computer-aided tongue image analysis which relies on the accurate rendering of color information. In Chaps. 9 and 10, the book introduces an optimized tongue image colorchecker and correction scheme which enhances the color consistency between different acquisition devices. It has long been a controversial topic that the TCM physician mainly explores the nonquantitative features in the traditional diagnosis process. To diagnose a wide range of health conditions, CTD should examine quantitative features of the tongue. From Chaps. 11 to 13, the book describes three tongue classification methods with excellent comprehensive performances.

In this book, some clinical applications based on the tongue image analyzing methods are also presented, for the show-how purpose, in the CTD research field. Case studies highlight different techniques that have been adopted to assist the diagnosis of diseases and health. From Chaps. 14 to 17, the book discusses relationships between diseases and the appearance of the human tongue in terms of quantitative features. In Part IV, we present case studies in the field of visual inspection for appendicitis, diabetes, and some other common diseases. Experimental results of the performance under different challenging clinical circumstances have shown the superiority of the techniques in this book.

The principles of tongue image analysis in this book are illustrated with plentiful graphs, tables, and practical experiments to simplify problems. In this way, readers can easily find a quick and systematic way through the complicated theories and they can later even extend their studies to special topics of interest. All the techniques presented in the book are well supported by experimental results using a large tongue image database, which was collected from 5,222 subjects (Over 9,000 images) by our dedicated developed image acquisition device. All these subjects were diagnosed (patient-subjects) or labeled (healthcare-subjects) into different health status (healthy, sub-healthy, and various diseases) in the hospital. To the best of our knowledge, this is the largest and most comprehensive database in the research community. This book will be of benefit to researchers, professionals, and graduate students working in the field of computer vision, pattern recognition, clinical practice, and TCM, and will also be useful for interdisciplinary research. We anticipate that physicians, biomedical scientists, engineers, programmers, and students of computers will find this book and the associated algorithms useful, and hope that anyone with an interest in computerized diagnostic research will find the book enjoyable and informative.

The book is the result of years of research on computational TCM diagnosis. Since 1998, under grant support from the National Natural Science Foundation of China (NSFC), Hong Kong Polytechnic University, and Harbin Institute of Technology, we have studied this topic. The authors would like to thank Dr. Zhaotian Zhang, Dr. Xiaoyun Xiong, and Dr. Ke Liu from NSFC for their consistent support to our research work.

Some of the material in the book, e.g., the tongue images and acquisition devices, has been under development for almost a decade. Portions of the book appeared in earlier forms as conference papers, journal papers, or experiments by my research group at The Hong Kong Polytechnic University and Harbin Institute of Technology. Therefore, these parts of the text are the newest updates based on our research.

I would like to gratefully acknowledge the Institute of Electrical and Electronic Engineers (IEEE) and Elsevier Publishers, for giving me permission to reuse texts and figures that have appeared in some earlier publications.

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Wang, Dr. Zhi Liu, and Dr. Zhenchao Cui, for their contributions to the research achievements on computational TCM diagnosis. It is also our honor to collaborate with them in this fascinating and ever-growing research field. I would also like to express my sincere thanks to all individuals and organizations who have contributed visual material for this book.

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Kowloon, Hong Kong David Zhang
June 2016

Contents

Part I
Background

Chapter 1
Introduction to Tongue Image Analysis

Abstract Tongue diagnosis is one of the most important and widely used diagnostic methods in Chinese medicine. Visual inspection of the human tongue offers a simple, immediate, inexpensive, and noninvasive solution for various clinical applications and self-diagnosis. Increasingly, powerful information technologies have made it possible to develop a computerized tongue diagnosis (CTD) system that is based on digital image processing and analysis. In this chapter, we first introduced the current state of knowledge on tongue diagnosis and CTD. Then, for the computational perspective, we provided brief surveys on the progress of tongue image analysis technologies including tongue image acquisition, preprocessing, and diagnosis classification.

1.1 Tongue Inspection for Medical Applications

Visual inspection of the human tongue, as a notable diagnostic approach, has been applied in various medical applications. In Western medicine, from the nineteenth century, the tongue has been found to be able to provide crucial signs for early diagnosis, and symptomatology of the tongue has been employed as an important index in human health and disease (Haller, 1982; Reamy, Richard, & Bunt, 2010). For instance, the color of the tongue can indicate Parkinson's disease (Matison, Mayeux, Rosen, & Fahn, 1982), nutritional deficiency (Jeghers, 1942), or even AIDS (Faria et al., 2005; Peng & Xie, 2006), and tongue fissure, as a typical kind of texture anomaly, has been found to be closely associated with Melkersson–Rosenthal syndrome (Ozgursoy et al., 2009), Down's syndrome (Avraham, Schickler, Sapoznikov, Yarom, & Groner, 1988), diabetes (Farman, 1976), and some other kinds of diseases (Grushka, Ching, & Polak, 2007; Zargari, 2006; Scheper, Nikitakis, Sarlani, Sauk, & Meiller, 2006; Han et al., 2016).

Moreover, in Traditional Chinese Medicine (TCM), as one of the most valuable and widely used diagnostic tools, the tongue has played an indispensable role for over 2000 years (Maciocia, 1995, 2004; Giovanni, 2015; Tang, Liu, & Ma, 2008; Fei, & Gu, 2007). Various kinds of tongue image features, including the tongue's

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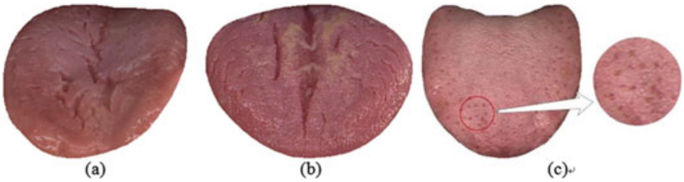

Fig. 1.1 Typical tongue image samples with different texture styles. **a** Is tongue fissure, **b** is tongue crack, **c** an image with a local substance (*red point*). Different texture styles convey various pathological information of internal organs, for example, *red point* is usually found on the tongue of subjects with appendicitis

color, texture, and geometrical shape, have been inspected and analyzed by TCM doctors in order to retrieve significant pathological information of the human body. For example, Fig. 1.1 shows three typical tongue texture styles: tongue fissure, tongue crack, and red point. These different texture styles have been discovered to be highly related with the health status of the human body. Yang, Zhang, and Nai-Min (2009) observed that people with irregular tongue crack features may be in an unhealthy state, and a red point is usually found on the tongue of subjects with appendicitis (Pang, Zhang, & Wang, 2005). In addition, the tongue shape is also used to indicate particular pathologies. Figure 1.2 presents some typical samples of various tongue shapes which are believed to convey pathological information of different internal organs (Huang, Wu, Zhang, & Li, 2010).

Among all features which can be extracted, the tongue's chromatic feature plays the most important role in evaluating a person's health condition (Nai-Min, Zhang, & Kuan-Quan, 2011). Tongue color is an essential attribute of the tongue body which

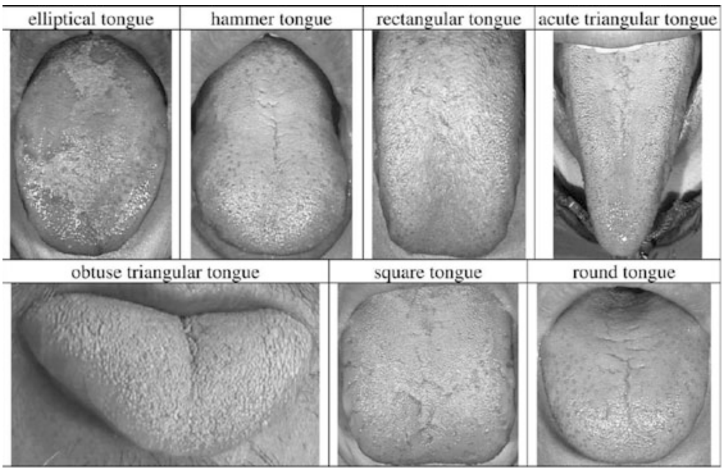

Fig. 1.2 Typical samples of various tongue shapes. Reprinted from Huang et al. (2010), with permission from Elsevier

possesses abundant medical information. According to the principle of tongue diagnosis in Traditional Chinese Medicine, TCM practitioners believe that pathological changes of internal organs can affect the color of the tongue body, and thus they can make a diagnostic decision based on this kind of color clue. Usually, tongue color is analyzed in two parts: substance color and coating color. Substance and coating are two essential parts of the surface of a tongue: tongue substance is usually the main body or the basis of a tongue while the coating is made up of materials floating above the tongue substance (Nai-Min, Zhang, & Kuan-Quan, 2011). The tongue colors of these two parts are different from each other, the tongue substance color is usually reddish colors including red, deep red, light red, and purple, and the tongue coating color is normally white, gray, black, or yellow. Figure 1.3 presents several typical images with various types of color features. Color patterns inspected from tongue images may lead to distinct diagnostic results. For example, a tongue body with a light red substance and white coating (as Fig. 1.3f shows) may indicate the healthy status of the person. Visual inspection of the human tongue offers a simple and immediate solution for medical diagnosis. If there is a severe disorder of the internal organs, tongue inspection instantly distinguishes the main pathological process. Hence, it is of great importance both in medical application and self-diagnosis to monitor one's state of health on a daily basis. In addition, tongue diagnosis is a kind of noninvasive diagnostic technique which accords with the most promising direction in the twenty-first century: no pain and no injury. Also, the tongue inspection process is inexpensive, and thus, this technique can be easily popularized.

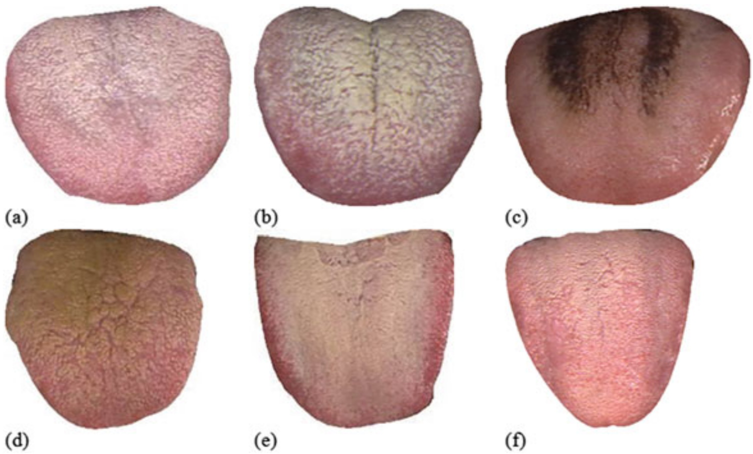

Fig. 1.3 Typical tongue images with various color patterns are critical for medical analysis in TCM. Colors of substance and coating in these images are **a** white and red, **b** gray and deep red, **c** black and deep red, **d** yellow and deep red, **e** gray and red, and **f** light red and white

1.2 Computerized Tongue Diagnosis System

As tongue inspection has a prominent role in both early warning signal provision and disease diagnosis, it has become more and more popular both in clinical medicine and in biomedicine. However, traditional tongue diagnosis has inevitable and intrinsic limitations which hinder its medical applications. First, since the tongue is visually observed by the human eye rather than recorded by a quantitative digital instrument, it is difficult or even impossible to quantitatively process tongue images, such as digital data storage, computer-aided image analysis and data transmission via the Internet for use in telemedicine applications. Second, the judging process of tongue diagnosis is subjective, which mostly depends on the medical experience and knowledge of the doctor. In other words, different doctors may achieve different results from the same visual expression on the human face. In view of this, attempts (Lukman, He, & Hui, 2008; Feng, Wu, Zhou, Zhou, & Fan, 2006; Chiu, 1996; Pang, Zhang, Li, & Wang, 2004; Chiu, 2000; Zhang, Pang, Li, Wang, & Zhang, 2005; Zhang, Wang, Zhang, Pang, & Huang, 2005) have been made to build an objective and quantitative tongue diagnosis system, i.e., a computerized tongue diagnosis system, which has been found to be an effective way to overcome the above problems.

By applying the technique of digital image processing (Sonka, Hlavac, & Boyle, 2014; Gonzalez & Wintz, 2007) and pattern recognition (Anzai, 2012; Duda, Hart, & Stork, 2012), the computerized tongue diagnosis system is proposed to make the inspection objective and repeatable so that it prevents human bias and errors. The schematic diagram of one typical computerized tongue diagnosis system is shown in Fig. 1.4. Similar to a typical pattern classification system, this system mainly consists of four modules: image acquisition, preprocessing, feature extraction, and decision-making. A lot of work has already been done concerning the development of these modules.

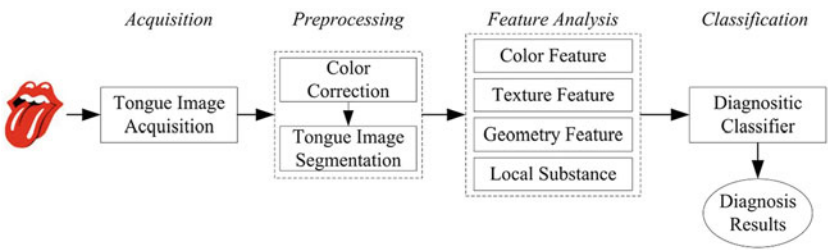

Fig. 1.4 Schematic diagram of a typical computerized tongue diagnosis system. This system mainly consists of four modules: image acquisition, preprocessing, feature extraction, and decision-making

1.3 Research Review on Tongue Image Analysis

The development of a computerized tongue image analysis and diagnosis system is believed to be an essential and effective way to solve the intrinsic problems in TCM which are unreliability and inconsistency. A lot of research work has been done on this topic to promote the standardization and modernization of tongue diagnosis in TCM.

1.3.1 Tongue Image Acquisition

Digital tongue image acquisition is the first step to realize computerized tongue diagnosis. With the development of digital imaging technology, the use of digital cameras in tongue inspection has been investigated for several years. According to the use of the illumination and imaging principle, there are generally two types of tongue image acquisition systems: the hyperspectral imaging system and the color imaging system.

The development of the hyperspectral tongue imaging system is generated by the growing interest in hyperspectral imaging in the research community (Chang, 2003; Kim, Chen, & Mehl, 2001; Mooradian, Weiderhold, Dabiri, & Coyle, 1998; Vo-Dinh, 2004; Zavattini et al., 2006). Researchers believe that by capturing images under illumination with a series of consecutive wavelengths (usually ranges of 400–800 nm with very narrow bandwidths), more valuable information could be retrieved for classification or recognition purposes. Liu and Li et al. developed a series of tongue imaging systems based on hyperspectral imaging technology (Du, Liu, Li, Yan, & Tang, 2007; Li, Wang, Liu, Sun, & Liu, 2010; Li, Wang, Liu, & Sun, 2010; Li, Liu, Xiao, & Xue, 2008). Also, related processing and matching algorithms were implemented (Liu, Yan, Zhang, & Li, 2007; Li & Liu, 2009; Zhi, Zhang, Yan, Li, & Tang, 2007). In their system, a series of tongue images was captured in 120 spectral over the waveband (400–1000 nm) at an interval of 5 nm. Hence a full 120-band hyperspectral image cube was acquired. Figure 1.5 shows two groups of hyperspectral images acquired from two persons. The left one was captured from a healthy person, and the other one was obtained from a patient with chronic cholecystitis.

Another type of tongue imaging system was implemented following the framework of a typical digital color imaging system. Tongue images were acquired under white illumination by various types of color imaging cameras. As these types of imaging devices are simple and easy to be implemented, researchers have paid more attention to this direction, and nearly ten imaging systems have been developed which possess various imaging characteristics (Pang et al., 2004; Chiu, 2000; Zhang et al., 2005; Yu, Jin, Tan, et al., 1994; Wong & Huang, 2001; Cai, 2002; Jang et al., 2002; Wei et al., 2002; Wang, Zhou, Yang, & Xu, 2004; Kim, Jung, Park, & Park, 2009; He, Liu, & Shen, 2007). These developed acquisition devices

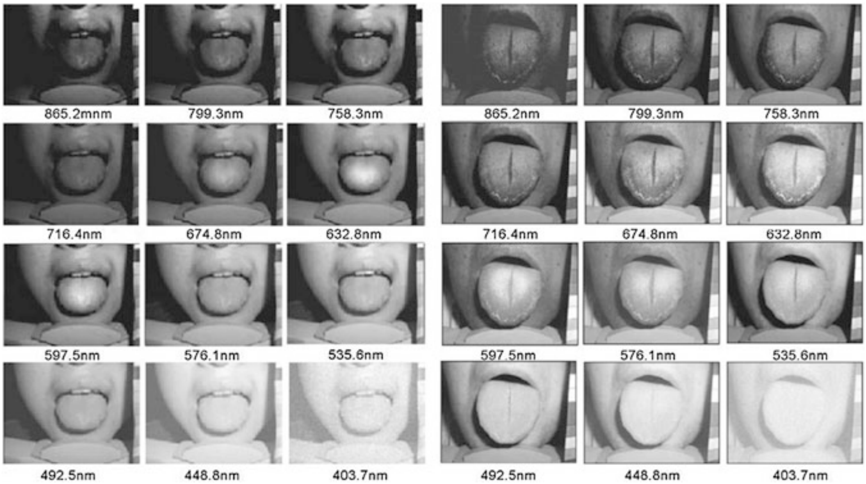

Fig. 1.5 Typical hyperspectral image samples of two individuals. These images were extracted between 403.7 and 865.2 nm wavelength. Reprinted from Zhi, Zhang, Yan, Li, and Tang (2007), with permission from Elsevier

mainly differ in the selection of lighting source and imaging camera. For instance, Wong and Huang (2001), Jang et al. (2002), and Zhang et al. (2005) utilized a halogen tungsten lamp as the lighting source, while Chiu (2000), Pang et al. (2004), and Wei et al. (2002), employed a fluorescent lamp. Due to the inconsistency among these devices, the quality of the captured tongue images varied.

1.3.2 Tongue Image Preprocessing

Tongue image preprocessing is essential for accurate and effective feature extraction. In computerized tongue diagnosis systems, two steps are commonly involved: one is color correction which aims to correct color variations caused by system components and to render the acquired tongue image into a device-independent color space. The other is image segmentation which extracts the tongue region from the original image which almost always includes lips, parts of the face, and the teeth.

1.3.2.1 Color Correction

Color images produced by digital cameras suffer from device-dependent color space rendering, i.e., the generated color information is dependent on the imaging characteristics of the specific camera. Furthermore, there are usually noises over the color images due to slight variations of the illumination. Therefore, in order to render the color image in high quality, color correction is necessary for accurate image acquisition and is often regarded as a prerequisite before further image analysis.

Research on color correction algorithms has been extensively conducted in the color science area. Several correction algorithms have been proposed for different tasks (Wang et al., 2004; Kim et al., 2009; He et al., 2007; Chang & Reid, 1996; Wandell, 1987; Finlayson, 1996; Barnard & Funt, 2002; Yamamoto et al., 2007; Vrhel & Trussell, 1999; Yamamoto & James, 2006; Vrhel, Saber, & Trussell, 2005). The polynomial-based correction method (LuoHong & Rhodes, 2001; Cheung, Westland, Connah, & Ripamonti, 2004) and neural network mapping (Cheung et al., 2004) are most commonly used. However, according to related literatures, there have been few published works that focused on the color correction of tongue images. In Zhang, Wang, Jin, and Zhang (2005), the authors proposed a novel color correction approach based on the Support Vector Regression (SVR) algorithm, and their experimental results confirmed the effectiveness of the proposed technique. Hu, Cheng, and Lan (2016) used the support vector machine (SVM) to predict the lighting condition and the corresponding color correction matrix according to the color difference of images taken with and without flash. In Zhuo et al. (2015), a kernel partial least squares regression based method was also proposed to obtain consistent correction by reducing the average color difference of their color patches.

1.3.2.2 Image Segmentation

Usually, in addition to the main tongue body, captured tongue images contain much other irrelevant information, such as lips, part of the face, and other non-tongue parts. Therefore, in order to improve the accuracy of tongue image analysis, we need to first extract the tongue region from the noisy background.

Image segmentation has been a classical problem for a long time, and a lot of segmentation algorithms have been proposed for distinct tasks (Sonka et al., 2014; Shi & Malik, 2000; Pal & Pal, 1993; Zhu & Yuille, 1996; Felzenszwalb & Huttenlocher, 2004; Shi, Li, Li, & Xu, 2014; Cui, Zhang, Zhang, Li, & Zuo, 2013; Wu & Zhang, 2015). In order to make these existing methods suitable for tongue image segmentation, researchers have made modification or revision of them. For example, based on the active contour model (Kass, Witkin, & Terzopoulos, 1988), Wu, Zhang, and Bai (2006) proposed a segmentation algorithm using the watershed transform to get the initial contour and converging with the active contour model to extract the tongue edge. Zhang et al. achieved this goal by employing the polar edge detector as the initial contour generator (Zhang, Zuo, Wang, & Zhang, 2006). Pang et al. proposed an algorithm named the bi-elliptical deformable contour (Pang et al. 2005a; Pang, Wang, Zhang, & Zhang, 2002) which combines a novel bi-elliptical deformable template (BEDT) with the traditional active contour model to improve the segmentation accuracy. Additionally, other segmentation algorithms have also been proposed. Wang, Zhou, Yang, and Wang 2004 applied the JSEG algorithm, which is a well-proposed method for unsupervised segmentation, for tongue segmentation. Yu, Yang, Wang, and Zhang 2007 and Ning, Zhang, Wu, and Yue 2012 developed their algorithms based on the gradient vector flow. All the above-proposed algorithms are reported to achieve acceptable performance.

1.3.3 Qualitative Feature Extraction

Based on the principle of tongue diagnosis in TCM, there are four main types of tongue features which can be extracted for medical analysis, i.e., color, texture, geometric shape, and local substance. Much work has been done to accurately and effectively extract these features (Cui, Liao, & Wang, 2015; Cui et al., 2014; Kim et al., 2014).

Tongue color is considered to be the most prominent feature which conveys plenty of valuable pathological information for medical diagnosis. Li and Yuen (2002) proposed several statistical metrics, including the color coordinate metric, color histogram metric, and sorted metric, to match the color content of different tongue images. Pang et al. extracted the mean and standard deviation of color values across entire tongue images to compare healthy samples with samples of appendicitis and pancreatitis (Pang et al., 2005a; Zhang et al., 2005). Following the diagnostic procedure in TCM, Huang and Li developed several tongue color centers which could be employed as class centers for disease classification (Li & Yuen, 2000; Huang & Li, 2008; Huang, Zhang, Zhang, Li, & Li, 2011; Huang, Zhang, Li, Zhang, & Li, 2011). Additionally, Wang, Yang, Zhou, and Wang (2007) considered the Earth Mover's Distance (EMD) (Rubner, Tomasi, & Guibas, 2000) as a classification metric for disease diagnosis.

Most traditional algorithms were directly applied to the task of tongue texture feature extraction. For instance, the Gabor wavelet was applied to extract Gabor Wavelet Opponent Color Features (GWOCF) for tongue image diagnosis (Yuen, Kuang, Wu, & Wu, 2000, 1999). The Grey Level Co-occurrence Matrix (Haralick, Shanmugam, & Dinstein, 1973) has also been utilized (Pang et al., 2005a; Zhang et al., 2005) to diagnose appendicitis and pancreatitis.

There has not been much research on the tongue geometrical shape and local substance features. Huang et al. extracted various geometric features, including tongue length, width, and diameter of the inscribed circle, in order to automatically classify tongue shapes (Huang, Wu, Zhang, & Li, 2010). The red point feature, which is a typical local substance feature, was extracted (Miao, 2007) using the Gabor wavelet. It is believed to be highly correlated to appendicitis. Also, Fungiform Papillae, as one kind of tiny substance in the surface of the human tongue, have been extracted by Gabor filter banks to predict various pathological conditions (Huang & Li, 2010).

1.3.4 Diagnostic Classification

After extraction of all kinds of features from tongue images, these features are supposed to be related to various pathological decisions including human health status or disease type. This is a classical pattern classification problem and many algorithms can be used for this task. As a powerful tool to effectively process fuzziness and uncertainty in the procedure of tongue diagnosis, the Bayesian network (Heckerman, 1997) was utilized for computerized tongue diagnosis in several studies (Pang et al., 2004; Wang & Zong, 2006; Ikeda & Uozumi, 2005). The reported experimental results show that this algorithm is suitable for tongue diagnosis and promising results were obtained. Moreover, in order to handle the fuzziness issue in tongue diagnosis, a diagnostic system for tongue analysis using fuzzy theory was developed (Watsuji, Arita, Shinohara, & Kitade, 1999). Five algorithms, i.e., ID3, J48, Naive Bayes, Bayes Net, and SVM, which are all implemented in WEKA, were compared to classify 457 tongue instances. The result shows that the Support Vector Machine performs the best among all these approaches (Hui, He, & Thach, 2007).

1.4 Issues and Challenges

Benefitting from the great improvement of image processing (especially gray image processing) and pattern classification technology in the past several years, several modules in the computerized tongue diagnosis system (as Fig. 1.4 shows) such as tongue image segmentation, texture feature extraction, and design of a diagnostic classifier have been greatly developed. Researchers started to pay more attention to these topics. Many related works could be found in imaging processing and the pattern recognition domain. However, several elementary but important issues have still not been well settled, which have impeded the development of this kind of system in recent years. First, although feature extraction and classification technology of tongue images have been well developed, tongue image acquisition technology, which is regarded as the basis of the computerized tongue diagnosis system, has not been greatly improved. Thereby, developed algorithms and obtained analytical results may not be reliable and convincing, and may suffer from limited applicability. Second, as the most important medical indicator, tongue color has not been well studied. For example, several important questions, including how to ensure that color information is captured in high fidelity, how to compensate for the noise and variations caused by the imaging system, what are the characteristics of tongue colors, and how to extract the most effective tongue color features for diagnostic purpose, have not been well answered. Figure 1.6 shows these most essential research topics which have not been well studied with green rectangular blocks.

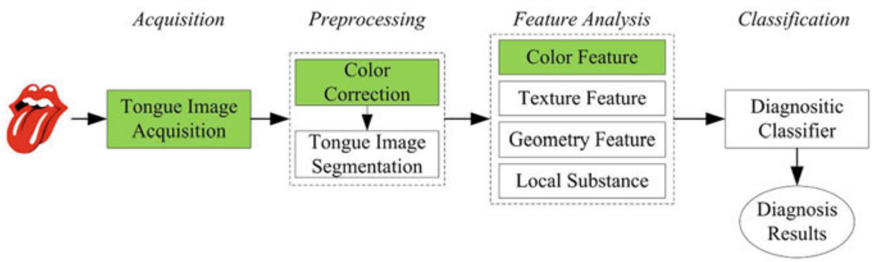

Fig. 1.6 Three modules which need to be further developed in the computerized tongue diagnosis system

1.4.1 Inconsistent Image Acquisition

Image acquisition is the most fundamental and vital part in the tongue diagnosis system. To date, nearly ten imaging systems have been implemented. However, due to the lack of fundamental research on guidance for designing tongue imaging systems, these systems were developed with inconsistent system components. Various types of imaging cameras and lighting sources which have different imaging characteristics have been utilized. Therefore, the quality of acquired tongue images varies considerably in these systems. Figure 1.7 shows three images acquired by the same camera for the same tongue body under three different kinds of lighting conditions. The color properties of these three images vary, and hence derived diagnostic results may be inconsistent even for the same tongue body. Also, images captured by the same camera at different times may be different due to inappropriate operation problems. Figure 1.8 shows images with different types of deficiencies of this type, i.e., inappropriate exposure and motion blur. This kind of imperfection would also greatly affect the analysis results. For instance, this kind of inconsistent image representation makes images captured by different devices noninterchangeable and nonsharable. Thereby, developed algorithms and obtained

Fig. 1.7 Three tongue images captured by the same digital camera under different illumination conditions from the same tongue body. Color inconsistency can be easily observed among these three images

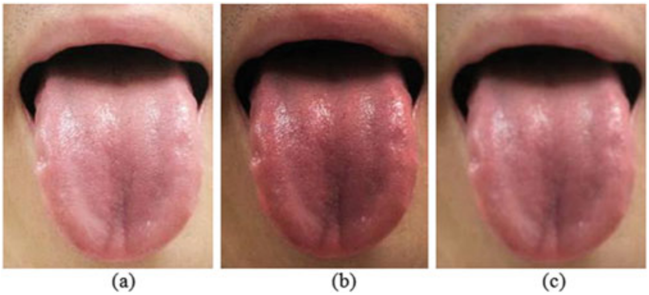

Fig. 1.8 Problem images acquired by a camera with inappropriate operation. **a** Over exposed image, **b** under exposed image, and **c** motion blur image

results on these captured images would be unstable and inconvincible. In view of this situation, it is crucial and urgent to conduct an in-depth requirement analysis in order to develop a high-quality and consistent tongue imaging system.

1.4.2 Inaccurate Color Correction

Tongue color correction is of great importance for high fidelity and accurate tongue image rendering. However, this issue has not yet been well addressed because of two main problems.

First, correction algorithms dedicated for tongue color correction have not been well developed. Although research on color correction methods in the color science area has been extensively conducted, these existing methods cannot be directly applied to tongue color correction because they are designed to process general imaging devices, such as digital cameras and cathode ray tube/liquid crystal display (CRT/LCD) monitors and printers, whose color gamut covers the whole visible color gamut and is much larger than the tongue color gamut. Therefore, in order to develop suitable tongue correction methods and thus to improve the correction accuracy, further optimization and improvement of the current correction methods need to be implemented and tested.

Second, besides the color correction algorithm, another problem which hinders the improvement of the accuracy of tongue color correction is the development of a tongue colorchecker. The colorchecker, which is usually utilized as a reference target for correction model training, plays a crucial role in the correction process. Currently, the Munsell colorchecker (MSCC) chart, which was designed in 1976 and regarded as the de facto standard is most commonly used in tongue color correction. However, this MSCC chart is designed to process natural images and is not specific for tongue colors, and thus it is too general to be applied for tongue color correction. Most colors in the MSCC chart are unlikely to appear in tongue images (e.g., green and yellowish green), and more theoretically, the color gamut (i.e., the range of colors) spanned by the MSCC chart colors is much larger than the limited color gamut of human tongue colors. In order to improve the accuracy of tongue color correction, developing a new colorchecker focused on tongue colors, i.e., a tongue colorchecker, is urgently needed to promote the correction performance so as to improve the tongue image quality.

1.4.3 Subjective Tongue Color Extraction and Classification

There are still many ambiguous and subjective factors involved in tongue image feature extraction. For example, because of the lack of knowledge about the tongue color distribution, and because the range of tongue colors and centers for typical color types cannot be objectively defined, the identification of different color types of tongue images is normally subjectively decided by TCM professionals based on their personal medical knowledge or experience (Wang et al., 2004, 2007; Kim et al., 2009; Kim, Do, Ryu, & Kim, 2008; Park, Lee, Yoo, & Park, 2016), which makes their obtained results unstable and imprecise. There are still no objective and precise definitions for each color category, such as what is the color center value of this "red" type and how to decide what kind of color belongs to the "red" type. Therefore, in-depth investigation of objective tongue color feature extraction is urgently needed in order to promote the development of computerized tongue image analysis.

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