journal homepage: www.intl.elsevierhealth.com/journals/cmpb

Image processing and machine learning for fully automated probabilistic evaluation of medical images

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ARTICLE INFO

Article history:
Received 22 December 2009
Received in revised form
22 June 2010
Accepted 28 June 2010

Keywords:
Machine learning
Coronary artery disease
Medical diagnostics
Multi-resolution image parameterization
Association rules
Principal component analysis

ABSTRACT

The paper presents results of our long-term study on using image processing and data mining methods in a medical imaging. Since evaluation of modern medical images is becoming increasingly complex, advanced analytical and decision support tools are involved in integration of partial diagnostic results. Such partial results, frequently obtained from tests with substantial imperfections, are integrated into ultimate diagnostic conclusion about the probability of disease for a given patient. We study various topics such as improving the predictive power of clinical tests by utilizing pre-test and post-test probabilities, texture representation, multi-resolution feature extraction, feature construction and data mining algorithms that significantly outperform medical practice. Our long-term study reveals three significant milestones. The first improvement was achieved by significantly increasing post-test diagnostic probabilities with respect to expert physicians. The second, even more significant improvement utilizes multi-resolution image parametrization. Machine learning methods in conjunction with the feature subset selection on these parameters significantly improve diagnostic performance. However, further feature construction with the principle component analysis on these features elevates results to an even higher accuracy level that represents the third milestone. With the proposed approach clinical results are significantly improved throughout the study. The most significant result of our study is improvement in the diagnostic power of the whole diagnostic process. Our compound approach aids, but does not replace, the physician's judgment and may assist in decisions on cost effectiveness of tests.

1. Introduction

Internal medicine and, in particular, cardiovascular medicine have a plethora of diagnostic imaging tests available to physicians to help identify various problems and abnormalities. Diagnostic imaging uses a variety of methods to create pictures of structures and function inside the human body. The choice of imaging technology depends on exhibited symptoms, the part of the body being examined, and its cost and availability. X-rays, computer tomography (CT) scans, nuclear medicine scans (including scintigraphy), magnetic resonance imaging (MRI) scans and ultrasound are all types of diagnostic imaging.

Many imaging tests are painless and easy. Some are slightly uncomfortable, as they require the patient to stay still for a long time inside a machine. Certain tests involve radiation, but these are generally considered safe because the dosage is very low. In some imaging tests, an implement (a tiny camera or other sensing device) is attached to a long, thin tube

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0169-2607/$ – see front matter
doi:10.1016/j.cmpb.2010.06.021

and inserted in the body. These procedures are quite unpleasant and often require anaesthesia. If possible, such procedures should preferably be replaced by less invasive ones.

Cardiovascular diseases, specifically coronary artery disease (CAD), are among the world's premier causes of mortality. Currently, cardiovascular disease diagnosis relies on diagnostic imaging tests that require expensive, specialized equipment and trained personnel (both technicians and physicians) for efficient operation. The goal of our research is to improve the diagnostics of CAD from a computational perspective. Our early research on this topic, conducted between 1995 and 1998 [1], showed that machine learning methods may enable objective interpretation of available diagnostic images and, as a result, increase the accuracy and reliability of the diagnostic process. Experiments conducted with various learning algorithms showed that these were able to achieve performance levels comparable to those of clinicians. The algorithms were also extended to deal with non-uniform misclassification costs in order to perform ROC analysis to control the trade-off between sensitivity and specificity. The ROC analysis showed significant improvements of sensitivity and specificity of machine learning algorithms compared to the performance of clinicians. The predictive power of standard tests can thus be significantly improved using machine learning techniques.

The main problem with this study was that all data, including evaluation of diagnostic images, had to be provided by expert physicians, this causing a major data acquisition bottleneck and a certain reluctance to accept the procedure in everyday practice. In the current study, we aim to alleviate the data acquisition problem by introducing algorithms for completely automatic evaluation (parameterization) of diagnostic images and for suggesting the most useful (informative) resolutions [2]. In this process we also introduce a feature extraction method (principal component analysis) that helps in achieving excellent results [3]. Our paper briefly describes the methodology used and relates the results of both studies. It also introduces assessment of the diagnostic power and the value of ROC analysis.

1.1. *Coronary artery disease*

Coronary artery disease (CAD) is the result of the accumulation of atheromatous plaques within the walls of the coronary arteries that supply the myocardium with oxygen. While the symptoms and signs of coronary artery disease are noted in the advanced state of disease, most individuals with coronary artery disease show no evidence of disease for decades as the disease progresses before the first onset of symptoms finally arises (a sudden heart attack). As the coronary artery disease progresses, there may be near-complete obstruction of the coronary artery, severely restricting the flow of oxygen-carrying blood to the myocardium. Individuals with this degree of coronary artery disease typically have suffered from one or more myocardial infarctions, and may have signs and symptoms of chronic coronary ischemia, including symptoms of angina at rest and flash pulmonary edema.

The usual clinical process of coronary artery disease diagnostics consists of four steps:

1. evaluation of signs and symptoms of the disease and electrocardiogram (ECG) at rest,
2. ECG testing during controlled exercise,
3. myocardial scintigraphy,
4. coronary angiography.

In this process, the fourth diagnostic level (coronary angiography) is considered to be the best reference method by physicians. Given that this diagnostic procedure is invasive and unpleasant for patients, as well as relatively expensive, there is an incentive to improve diagnostic performance of earlier diagnostic levels, especially of myocardial scintigraphy [4,1]. Approaches used for this purpose include applications of neural networks [5–7], expert systems [8], subgroup mining [9], statistical techniques [10], and rule-based approaches [11].

In our study, we focus on various aspects of improving the diagnostic performance of the third diagnostic level. Myocardial perfusion scintigraphy consists of acquiring a series of medical images using an inexpensive and non-invasive procedure when the patient is at rest and during a controlled physical exercise. Subsequently, expert physicians use their medical knowledge and experience to manually describe (parameterize) and evaluate the images, often with the help of image processing capabilities provided by various imaging software tools.

Our first study was based on patients' data compiled entirely by physicians—either by extracting data from medical records, or from test results (ECGs and scintigraphic images). Using these data, our machine learning algorithms showed excellent diagnostic accuracy and reliability in the diagnosis of coronary artery occlusions [4].

The current study presents an innovative alternative method to manual image evaluation. The method consists of automatic multi-resolution image parameterization, based on texture description with specialized association rules, coupled with image evaluation with machine learning methods. Since this approach yields a large number of relatively low-level features (though much more informative than simple pixel intensity values), we have used additional dimensionality reduction techniques, either by throwing away some features (feature selection), or combining them into more informative, high-level features (feature construction). Our results show that multi-resolution image parameterization equals or even outperforms physicians in terms of the quality of image parameters. Using automatic image description parameters, diagnostic performance can be significantly improved with respect current clinical practice.

2. Methods

2.1. *Image parameterization*

Image parameterization is a technique for describing bitmapped images with numerical parameters—features or attributes. Traditionally, popular image features are first- and second-order statistics, structural and spectral properties, and several others. Image parameterization is used in quality control, identification, image grouping, surveillance, image storage and retrieval, and image querying. Over