Medical Validation and CBIR of Spine X-ray Images over the Internet

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ABSTRACT

As found in the literature, most Internet-based prototype Content-Based Image Retrieval (CBIR) systems focus on stock photo collections and do not address challenges of large specialized image collections and topics such as medical information retrieval by image content. Even fewer have medically validated data to evaluate retrieval quality in terms of precision and relevance. To date, our research has reported over 75% relevant spine X-ray image retrieval tested on 888 validated vertebral shapes from 207 images using our prototype CBIR system operating within our local network. As a next step, we have designed and developed an Internet-based medical validation tool and a CBIR retrieval tool in MATLAB and JAVA that can remotely connect to our database. The retrieval tool supports hybrid text and image queries and also provides partial shape annotation for pathology-specific querying. These tools are initially developed for domain experts, such as radiologists and educators, to identify design issues for improved workflow. This article describes the tools and design considerations in their development.

Keywords: CBIR, Medical Image Retrieval, Validation, Shape Similarity, Client-Server, NHANES II, Spine X-ray, Bone Morphometry, Medical Multimedia Database

1. INTRODUCTION

Content-Based Medical Image Retrieval (CBMIR) is an area of growing research interest. After several years of research efforts in retrieval of stock photo collections there is growing interest in the management, indexing, and retrieval of specialized image collections such as medical images[1-3]. This poses significant research challenges since the results from research efforts in CBIR of stock photo collections are not immediately applicable to these specialized collections. Two classes of CBMIR can be identified based on the ability of the algorithms to classify a collection of images. If the collection contains images from different modalities with different anatomy imaged in different views, a high level classification algorithm can separate them into relevant groups. Within each group of images of the same modality, anatomy and view, a low level classification algorithm could identify relevant objects of interest and identify the pathology. The extracted features could then be used to index images and provide CBIR capability for their retrieval. This aspect of image indexing is of current interest in our research.

At the U.S. National Library of Medicine we maintain a collection of 17,000 digitized spine X-ray images of the cervical and lumbar spine in sagittal view from the second National Health and Nutrition Examination Survey (NHANES II). The images come with over 2000 text fields of survey data that include demographic information, health questionnaire, and medical reports. Such spine X-ray images are of great interest to bone morphometrists and radiologists since they exhibit pathologies such as anterior osteophytes (AO), disc space narrowing[4] (DSN), subluxation[5] and spondylolisthesis that are detectable consistently and reliably by vertebra boundary shape. Other pathologies such as vertebral fractures, ossification of posterior longitudinal ligament (OPLL), spinal stenosis caused by posterior osteophytes, tumors, and osteoporosis may also be detected from this dataset.

We have made NHANES II image and text data set available to researchers and educators through a variety of Internet accessible visualization and retrieval tools. These data are currently available through our Web-based Medical Information Retrieval System (WebMIRS)[c, 1]. The images are also independently available via FTP from our Website. A major goal of the project is to enable CBIR for such large biomedical image collections by specifying image features defining the anatomy, and in particular, the pathology of interest in them. Our efforts in this direction have resulted a

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[c] WebMIRS is available at http://archive.nlm.nih.gov/proj/webmirs.php

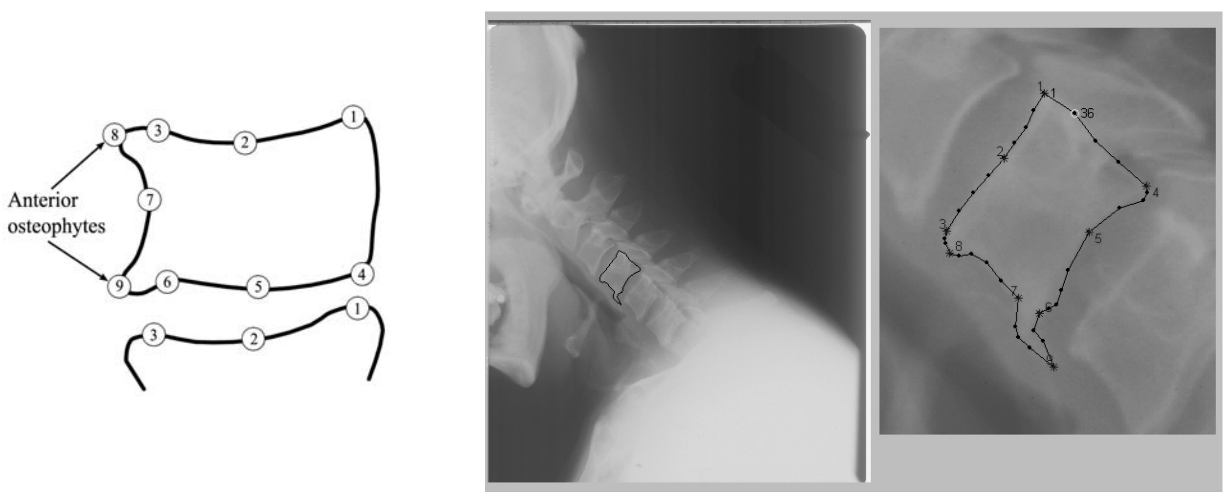
comprehensive CBIR tool that permits indexing of these images by vertebral shape which is segmented through user assisted optimized orthogonal active-contour segmentation, indexing using optimized KD trees using shape embedding, and their retrieval by whole and partial shape matching. More recently, we have incorporated the use of relevance feedback into shape retrieval for vertebral shape[6-8]. These tools, until recently, had been developed as a part of a stand-alone system that works within a local network and was not designed for use over the Internet.

In order to evaluate retrieval performance, a part of the image collection was validated by a medical expert to indicate type and severity of AO[9]. We obtained fairly high retrieval relevance results for distinctly severe and mild cases. However, much confusion was observed for images exhibiting pathology that fall in between slight and moderate, and moderate and severe categories. In order to develop robust algorithms for pathology detection, image indexing, and content-based image retrieval, it is necessary to obtain a large collection of medically validated images from multiple experts. Our research goals are (1) to expand the medical validation to the entire image set by cross validation from multiple geographically separated board-certified medical experts to include type and severity for all three pathologies mentioned above and multi-resolution vertebral boundary segmentations; and (2) to conduct medical validation of retrieval results on shape-based queries, and perform usability studies on medical CBIR systems.

This article discusses the development of a medical validation tool and a preliminary version of the CBIR tool that operate over the Internet. It discusses the design considerations and technical challenges faced when developing software for each tool. In section 2, we provide additional background on the project. The section describes the characteristics of the spine X-ray image and the pathology of interest, and methods for image segmentation and data collection. Section 3 describes the image validation tool, its design characteristics, features and capabilities. Section 4 describes the Web-enabled CBMIR. Conclusions and future work are given in Section 5.

2. BACKGROUND

NHANES II was conducted by the National Center for Health Statistics during 1976-1980 and included participants aged 6 months to 74 years. For the NHANES II survey, the records contain information for approximately 20,000 participants. Each record contains about two thousand data points, including demographic information, answers to health questionnaires, anthropometric information, and the results of a physician's examination. In addition, approximately 10,000 cervical spine and 7,000 lumbar spine X-ray films were collected on survey participants aged 25-74. No X-rays were taken on pregnant women, and no lumbar X-rays were taken on women under 50. The pathologies of interest on these X-rays were osteoarthritis and degenerative disc disease.



(a) (b)

Figure 1. (a) Anterior Osteophytes illustrated on vertebral body outline. Points marked indicate regions of interest. (b) Spinal X-ray image showing segmented vertebra and a localized view showing inferior AO on vertebra with 36 boundary points superimposed.

The NHANES II X-rays serve as a rich data source for research into pathology-based retrieval of biomedical images. For example, an osteophyte, a bony protuberance on normal bone surface, is a characteristic feature of degenerative joint disease of the spine. After careful study of the NHANES II image collection medical experts have previously determined that the anterior osteophyte (AO) is a pathological feature that can be reliably and consistently detected in the images, along the anterior superior or inferior edges of the vertebral bodies. An example of superior and inferior AO is illustrated in Figure 1(a) and shown in 1(b). Points 2-3-8-7 describe a superior anterior osteophyte on a sagittal spinal X-ray and points 7-9-6-5 describe an inferior anterior osteophyte. In such cases, only a small interval along the vertebral boundary is pertinent to the pathology. Methods for querying vertebrae through visual means for pathology, such as AO, would be immensely useful to epidemiologists, radiologists, bone morphometrists, medical students, and researchers of musculoskeletal diseases.

CBIR on spine X-ray data: To enable CBIR on spine X-ray images appropriate features need to be captured from the vertebral image. In this case, the pathology in a vertebra can be captured in the outline of its body seen in a 2D projection in the sagittal spinal X-ray. Analysis of this outline could enable computer methods to retrieve vertebral images that are pertinent to a visual query expressed with a user-sketch or an example image. These features then need to be indexed along with the supporting text information. For retrieval, the same features are extracted from the query image and then matched with the indexed features. These and other steps in the development of CBIR were implemented as separate tools as a part of our ongoing research efforts [6]. CBIR3 is our first step toward a networked CBIR system that is extensible, supports a centralized database, and most of the tools developed in our research. It has the capability to add new tools with relative ease. Section 4 in this article describes the developmental decisions for network-enabling CBIR3.

Medical validation: It is important to obtain medical validation data on the segmented boundaries of vertebral bodies and pathologies indicated by them. Collection of this data enables validation of retrieval performance and assists in development of robust algorithms that reflect the typical queries posed by the targeted user community. Till recently the anterior osteophytes were our primary focus for shape-based retrieval in this project. Our interaction with a group of board certified radiologists has revealed that with use of image enhancement techniques, it may be possible to discover the existence of other pathologies such as spinal stenosis caused by posterior osteophytes. Correlating these pathology labels with segmented image features and available survey participant health data can be used to build knowledge models and further enhance features of this multimedia database. These steps can help lead traditional CBIR research to a tool that can help further research and education in a particular field of medicine.

Image compression: Delivery of medical images over the Internet has always been a challenging problem. On one hand, use of popular and lossy compression algorithms can undermine the diagnostic value of the image. Development of specialized algorithms for each class of images, on the other hand, can limit their use and require development of a new compression technique for every class of images. Research with our collaborators has resulted in the development of a new wavelet-based hybrid vector-scalar quantization (HVSQ) compression algorithm which builds a codebook on the fly for a particular image providing a significant compression while retaining acceptable image quality[10, 11]. The method is applicable to color images as well as gray level images. Although vector quantization techniques exhibit superior performance when compared with their scalar counterparts, certain problems such as such as high complexity, slow processing time, lack of exact bit-rate control and need for codebook generation, associated with vector quantization have prevented their use in a standard codec. The proposed HVSQ exploits the hybrid nature a combined vector-scalar quantization technique while achieving exact bit rate control, preserving high color quality, and reducing complexity with a novel embedded codebook generation and on-line codebook training scheme. We have incorporated this codec into our software enabling low bandwidth connections to the Web to use the tool.

3. IMAGE VALIDATION TOOL

The image validation tool was developed to collect ground truth data on the digitized spine X-ray images from NHANES II. In addition, it enables verification of the segmented vertebral boundaries and collection of pertinent pathologies from the image as a whole, in addition to those local to the vertebral body. The tool, shown in Figure 2, is designed to allow content experts to login into our database and review image and pathology data and provide necessary updates. The software can operate in an offline or online mode and need only connect to exchange data. It has been developed using JAVA and continues to evolve based on expert suggestions.

In developing a medical validation tool, it is essential to take into account typical practices of the radiologists and other medical experts providing validation data. For example, a brightness-contrast leveling tool is often assumed to exist on such software as a response to vertical drag movements of the mouse with a (user-selectable) mouse-button depressed. Other image enhancement tools are unsharp masking and image negation. Our interaction with experts has enabled us to develop software that provides a traditional interface and could help in minimizing the learning curve. It also takes into account that the radiologists are providing this data while caring for their patients and may be interrupted during the validation process. The system regularly saves their work and if necessary can return them to their last completed action.

The system is shown in the schematic on Figure 3. It consists of a JAVA servlet and an image server on the server side and the validation tool on the client side. The client tool operates in both stand-alone and online modes. It starts up in stand-alone mode and the user can login to the remote server to download image and text records. These records can be obtained as individual items or can be downloaded in selectable batch sizes. If the latter is selected, then future operations of the client can be performed in stand-alone mode until all images and records have been reviewed. After completing the batch the user uploads all validated records which are verified by the service manager. Only the validated text records and image segmentation data are uploaded. Such batch mode operation allows the medical experts to validate images on their own time while disconnected from the Internet. In this case, the user may need to login to the server again for the data transactions.

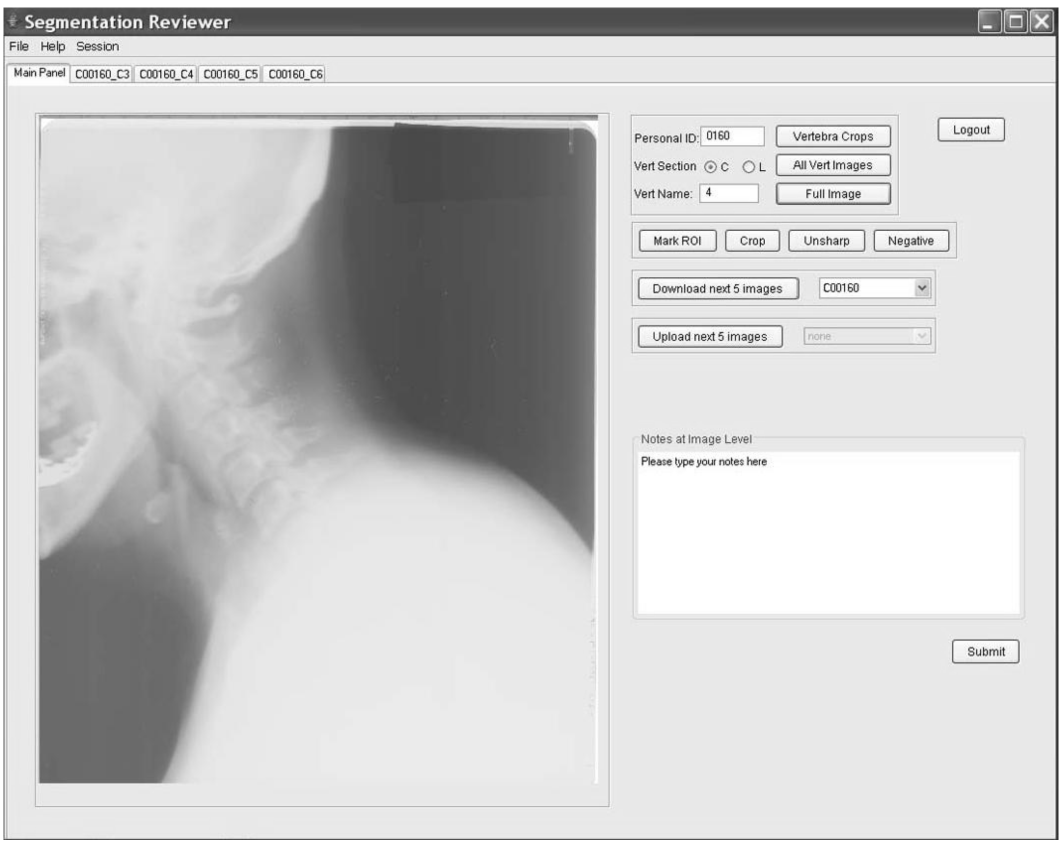


Figure 2: Screen shot of main window in medical validation tool and segmentation reviewer showing a whole cervical spine X-ray and some image enhancement controls.

For each image the user is shown the image on a tabbed interface with the entire image on the main tab, as in Figure 2. Here the user can mark regions of interest (ROI) and perform image enhancements to better view pathology of interest. Image enhancement tools include a leveling tool, unsharp masking tool that operates in a cumulative fashion, and image negation tool. These tools are commonly used by radiologists in their typical workflow. This tab also permits image level comments to be recorded. Individual vertebral images are visible through a button on this main panel. The viewport for each vertebra is computed from segmented vertebral boundary data coordinates that are stored in the server database. Currently, the dimensions of this viewport are arbitrarily set to extend 50 pixels on all sides of the minimum and maximum *x* and *y* (row and column) values of the segmented vertebral boundary. Since the vertebral segment is not cut and saved as a separate image, it is possible to allow the user to expand his view to include neighboring vertebrae by adjusting the crop coordinates. Currently, these values, the top left corner coordinates, and width and height are entered manually, seen in the middle of the screen shot in Figure 4. In consultation with the medical experts we are planning to enhance this viewing technique to a starting with a multiple vertebra view of spine while highlighting the vertebra under investigation. This view would enable the medical experts to make a better judgment on the pathology. They could then zoom into the (highlighted) vertebra of interest using the proposed mouse-based magnification tool. This advance will obviate the need for our current coordinate-based viewport resizing approach.

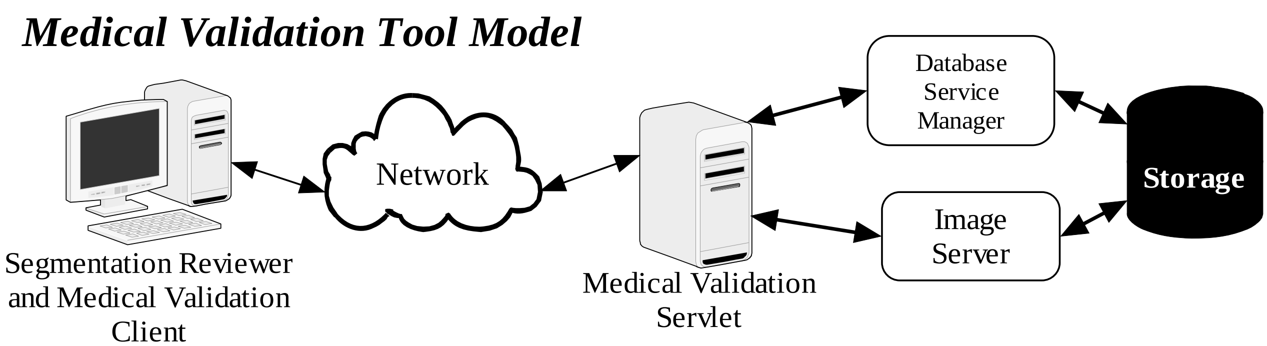


Figure 3: Schematic depicting various components enabling collection of medical validation data.

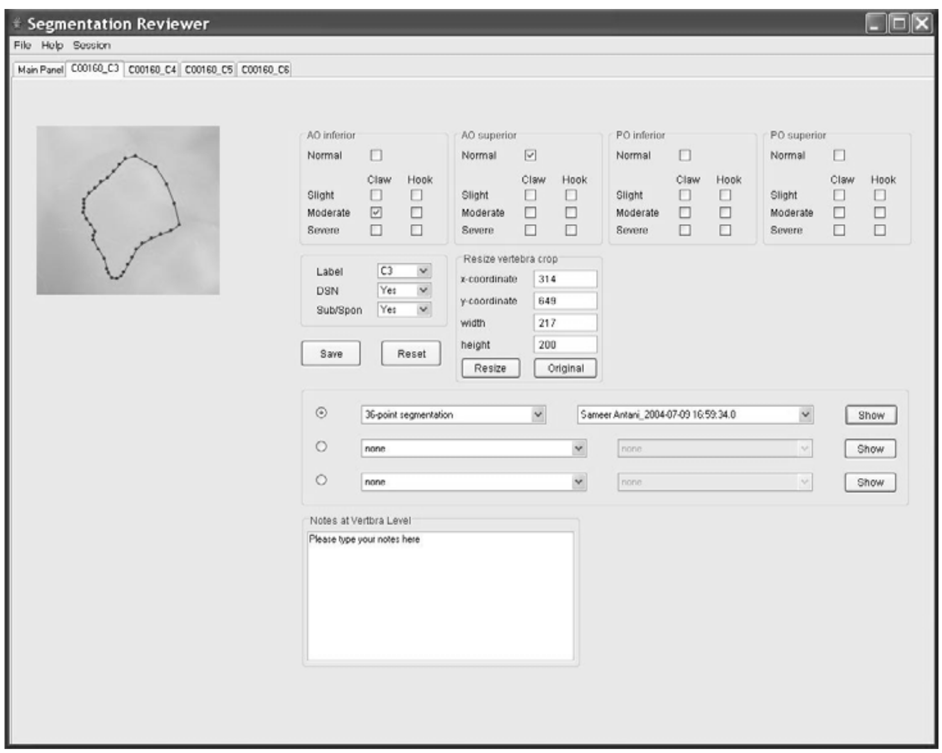
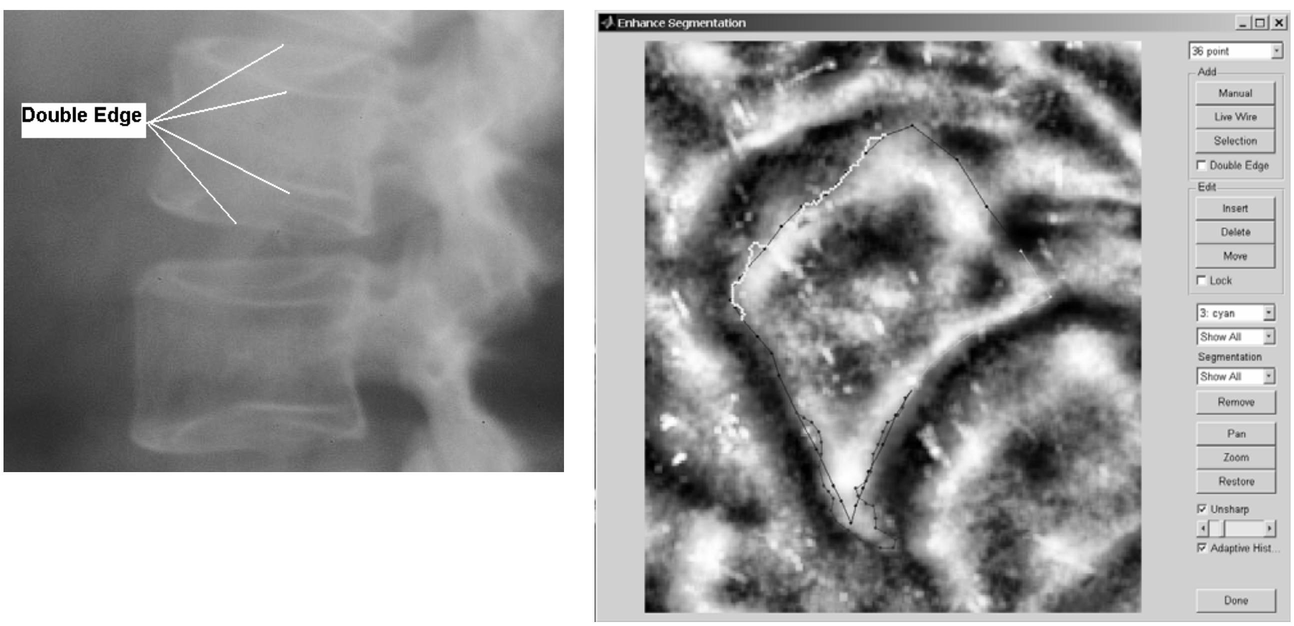


Figure 4: Screen shot of vertebral tab panel depicting a cropped vertebra with the segmented boundary as overlay. It also shows various pathology check boxes and notes area.

On the vertebra pathology examination panel, shown in Figure 4, the medical expert can enter data about four types of pathologies and comment about others not covered by the provided check-boxes. The pathology categories provided are anterior and posterior osteophytes, disc space narrowing, and subluxation and spondylolisthesis. For the osteophytes, they can either by normal or have three grades of severity, viz.., slight, moderate, and severe. Each can be of traction or claw type. It is possible to mark both types of pathology for vertebrae with osteophytes of *slight* severity. This indicates that the expert was unable to determine the type of degenerative growth. For moderate and severe only one of the two types may be marked since it is expected that a clear judgment can be made for these severities. Overall, each osteophyte location can have only one severity grade. For disc space narrowing, the expert can indicate mild, moderate, or severe. The tool also provides a measuring tool for measure distances between objects. In certain cases, this tool could be used to measure the narrowing. For subluxation and spondylolisthesis, both of which indicate disk slippage, similar mild, moderate, and severe selection criteria are provided.

Often, a vertebral boundary computed by (semi) automated image processing methods and having received only technical level oversight isn't medically valid. Thus, an essential task of this validation process is verifying that these boundaries are indeed a true representation of the anatomy. Additionally, for the fixed point boundary distributions, viz., the 9-point and 36-point boundaries, it is essential that the points are located at appropriate locations. For example, in the 9-point boundary layout, shown in Figure 1(a), points 1, 3, 6, and 4 are indicative of the four "corners" of the vertebral body as seen in a projective sagittal view. These and other points are often used as anchors in our shape matching and their correct location is important to proper system performance. The experts can modify boundary-point position by moving each point as necessary. In addition the medical expert can also select one or more valid boundary representations from the multiple segmentations often available for each vertebra. A segmented boundary shape is identified by the segmenting person identifier and creation date. The software provides a way to show the experts each shape on the X-ray image and up to three shapes can be overlapped. It is also possible to turn off the lines connecting the boundary points to get a clearer view of the outline with respect to the image edge.



(a) (b)

Figure 5 (a) A cropped section from a lumbar X-ray showing two vertebrae exhibiting double edges. (b) Edge markup software for marking double edges and other pathologies not expressed by the 9- and 36-point boundary segmentations.

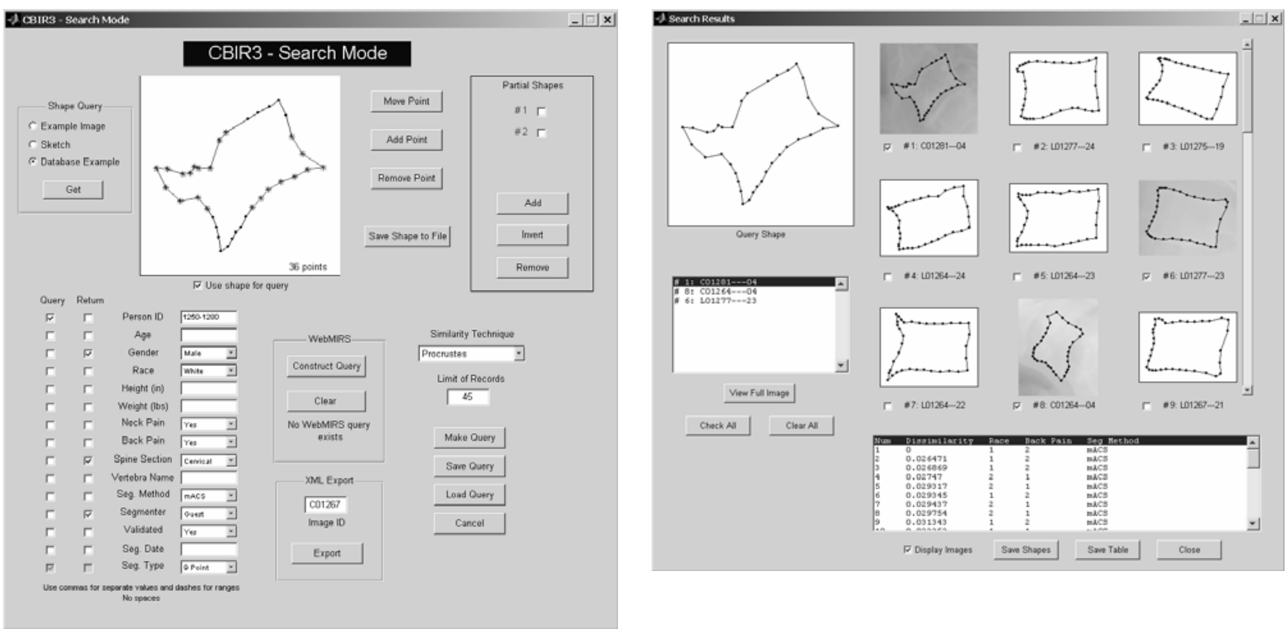
A unique aspect of our CBIR data is that images are acquired through projective imaging where the beam source is a point. This causes three dimensional objects that are not parallel to the beam to cast edge shadows for both near and far edges on both inferior and superior surfaces. An example of such a view is shown in Figure 5 (a). In such cases it is insufficient to pick any one edge arbitrarily. Doing so can cause incorrect measurement of anterior and posterior vertebral heights and also possibly create the appearance of an AO where there is none. To alleviate this problem, we urge the radiologists to mark the true inferior and superior edge as an imaginary line going through each surface.

Additionally, they are asked to also mark the double-edges as seen in the image. For this purpose we provide them with a separate utility for marking these edge enhancements and indicating that the edges denote a surface. The lateral (left or right) sides of vertebral edges can also be marked if they can be clearly determined from the image. The same utility, shown in Figure 5(b), can mark other features on the edge that cannot be correctly marked with the fixed point boundary models. The screen shot shown above is from the tool as developed in MATLAB. We are currently developing a JAVA version for it.

4. WEB-ENABLED CBMIR

Not only is it important for the domain experts to validate image segmentations and provide pathology data, it is also imperative that they verify and validate the retrieval. In the past, our research prototype was tightly coupled with our databases and systems within our internal network. For us to obtain expert comments was challenging since it required the physical presence of the users at our facility or replication of the entire collection at the remote facility. There was a defined need for us to enable Internet or Web-based access to our programs and data while enabling expert feedback. These goals have led to the development of our first prototype Internet accessible content-based medical image retrieval system.

The new system is based on the CBIR3 prototype reported earlier[6]. It is developed in JAVA and MATLAB and at present requires installation of a MATLAB compiled client at the user end and is currently limited to Microsoft Windows platform. The text and image databases accessible through CBIR and Image servers described earlier continue to reside at the National Library of Medicine. Two major advances over CBIR3 are remote usability and optimally indexed vertebral shapes[7].



(a) (b)

Figure 6. (a) Query screen for CBIR3. (b) Sample result from a hybrid text-shape query. Note capability to view vertebra image crops, full image and save results as XML.

The retrieval system permits both text and image queries. Text queries can be posed as a set of limited fields available on the query screen shown in Figure 6(a) or as a rich SQL-like query in a modified version of the WebMIRS system. Image queries can be combined with text queries which provide limits on the range of images and vertebral shapes processed by the image feature matching component of the system. Image queries may be posed as sketch, as shown in Figure 6(a), or as an image example. The system supports two shape matching techniques, viz., a shape matching method based on Shape-Space Theory[7] using the Procrustes Distance and another using Fourier Descriptors[6]. Both methods support both partial-shape and whole-shape queries. The results are displayed in order of increasing dissimilarity of vertebral shapes as shown in Figure 5(b). Selected text fields from these matching shapes are also displayed and the entire health record may be obtained by selecting any individual vertebral shape.

Limitation in current Web-based CBMIR: While the Web version of our CBIR system contains most features found in our CBIR3 prototype, it does have some interesting differences. Since the Web-version supports optimal indexed search trees for vertebral shapes, linkages between text record numbers and segmented vertebral boundaries are now broken. The vertebral segmentation data was originally hosted in the text database and was limited to linear searches. While optimal indexing significantly improves search times a hybrid text and image query cannot be *joined*. For the present we make different searches on these databases and present results separately. As a result, there may be text records that do not have corresponding images and there may be images that do not entirely match the text criteria. Text and image fusion is a challenging problem and remains an area of research for us.

5. LESSONS LEARNED AND FUTURE WORK

The article describes design and development of a Web-enabled medical validation client and CBIR tool. While neither tool can be currently generalized for use with a variety of image types, it is our intent to build such tools that can be easily modified for such different image types by learning from the design and use of such tools. Lessons were learned in both design and developmental aspects of these tools and are important for any project of similar nature. They include concepts in project and workflow planning, software and GUI design, and software engineering. Involving primary users, who may be domain experts, early on in the development and planning of such software is very helpful. Obtaining information about their typical workflow and obtaining a list of desirable features significantly improves long-term benefits from the data collection and validation efforts. Some examples of add-ons and modifications in our software resulting from such efforts include mouse-based image enhancement tools, batch-mode operation, and tools for reorienting users interrupted during the validation process.

Several enhancements are planned for these tools which aim to reduce expert burden in medical validation and improve user-experience in Web-based CBMIR. We also expect to expand other components of our stand-alone prototype system that include several image segmentation algorithms, and image indexing component to Internet-based systems in the future. A major hurdle in this task will be redevelopment of specialized routines in a cross-platform language such as JAVA. In general, we expect that the contributions from this work will enable (1) a medically validated dataset valuable for evaluating retrieval quality and performance, training similarity matching algorithms, and research in relevance feedback based retrieval; (2) a thorough evaluation of the value and usability of CBIR in a medical setting, and issues related to the functionality and graphical user interface design; (3) formation of general principles for design and development of similar tools that could allow validation and retrieval of images of different anatomy in different modalities which may have different set of pathologies; and finally (4) furthering research in image and text data mining and data fusion specific to problem of content-based image retrieval.

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