Interpreting Ultrasound Images for Accurate Epidural Needle Insertion

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1 Background

This work presents development and testing of image processing algorithms for the automatic detection of landmarks within ultrasound images.

The aim was to automate ultrasound analysis, for use during the process of epidural needle insertion. For epidural insertion, ultrasound is increasingly used to guide the needle into the epidural space. Ultrasound can improve the safety of epidural and was recommended by the 2008 NICE guidelines (National Institute for Health and Care Excellence). Without using ultrasound, there is no way for the anaesthetist to observe the location of the needle within the ligaments requiring the use of their personal judgment which may lead to injury. If the needle stops short of the epidural space, the anaesthetic is ineffective. If the needle proceeds too deep, it can cause injuries ranging from headache, to permanent nerve damage or death.

Ultrasound of the spine is particularly difficult, because the complex bony structures surrounding the spine limit the ultrasound beam acoustic windows [1]. Additionally, the important structures for epidural that need to be observed are located deeper than other conventional procedures such as peripheral nerve block. This is why a low frequency, curved probe (2-5 MHz) is used, which penetrates deeper but decreases in resolution.

The benefits of automating ultrasound are to enable real-time ultrasound analysis on the live video, mitigate human error, and ensure repeatability by avoiding variation in perception by different users.

Previous ultrasound image processing for epidural research used speckle image enhancement with canny and gradient based methods for bone detection [2]. A clinical trial with 39 patients had success detecting the ligamentum flavum (LF) from ultrasound by algorithms in 87% of patients.

Echogenic needles and catheters are now becoming available which are enhanced for extra ultrasound visibility. The Epimed UltraKath ULTRA-KATH™ [3] has a patented design to maximize visibility under ultrasound [4]. The Echogenic Tuohy Needle also includes imprints on the needle tip that reflects ultrasound, allowing for better visualization. Curved needles can also be detected in 2D ultrasound images [5].

Fig. 1. Echogenic Catheter fits inside Tuohy needle [3].

2 Methods

The most important landmarks to detect for epidural insertion are: identify the sacrum, detect which vertebral level from L1-L2 to L4-L5, label the vertebral body, locate articular process, measure the angle from center line and measure the depth to epidural space in centimeters [4].

Based on these requirements, our algorithms were designed with three main objectives:

(1) **Identification of lumbar level**.
  (1.1) Identification of the L3-L4 interspinous region.
  (1.2) Identification of sacrum.
(2) **Identification of ligamentum flavum**.
  (2.1) Identification of dura.
  (2.2) Measure the depth of ligamentum flavum from skin.
(3) **Identification of Spinous process** (Midline).

Three main image processing techniques were applied in our algorithms:

(i) Normalized Cross Correlation image processing technique was used to normalize the images because the brightness of the ultrasound image and template can vary due to acoustic and exposure conditions.

(ii) Hough transform is used to identify positions of arbitrary shapes, most commonly circles or ellipses. The linear Hough transform algorithm uses a two-dimensional array, called an accumulator, to detect the existence of a line described by Eq. 1. The dimension of the accumulator equates to the number of unknown parameters, i.e., two, considering quantized values of r and θ in the pair (r, θ).

$$\boldsymbol{r} = \boldsymbol{x} \cos\theta + y \sin\theta \qquad (1)$$

(iii) Template Matching is used with a template of a region of interest (ROI) is stored and matched with an input image. The algorithm centers the template on an image point and counts how many points in the template match those in the image. The procedure is repeated for the entire image. At the point that led to the best match, the maximum count is deemed to be the point where the shape lies within the image.

3 Results

(1) Identification of lumbar level and sacrum

The lumbar level identification is implemented for L3/L4 which is popular for needle insertion because it provides the largest interspinous space. This algorithm uses template matching. An appropriate template was cross-correlated with the image and stored in a matrix. The matrix maxima form can identify the region of interest containing lumbar levels. A threshold value is used to avoid false detections.

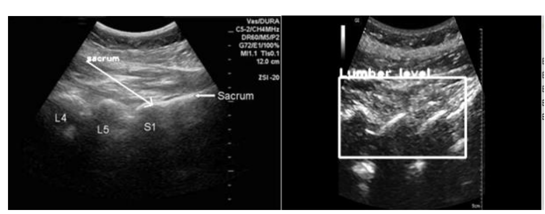

Fig. 2. (a) Detection of L3-L4 interspace. (b) detection of sacrum and counting the lumbar levels.

Fig. 3. Detection of Sacrum in three ultrasound images

Fig. 2a shows the detected lumbar levels after cross correlation. The lumbar levels were identified by the saw tooth pattern.

In Fig. 2b, sacrum (S1) is identified as a continuous hyper echoic parallel to the skin. To locate the L3-L4 interspinous region, we count backwards from S1, L5, L4, L3. Fig 3 shows three successful sacrum detections.

(2) Identification of ligamentum flavum.

Two algorithms were tested: (1) Hough transform, (2) template matching. The best result was template matching. The template is shown in Fig. 4a which worked successfully on ultrasound images as shown in Fig. 4b.

Result of cross correlation between the template (Fig 4a) and the input image is shown in Fig. 5, displaying the weight sum of pixels, where the peak contains ligamentum flavum.

Some failures occur when the template is too large or small compared to the input image. This was solved by using a greater number of template in different sizes and different types. Failures due to noise in the image were solved by using image enhancement methods.

To measure the depth of ligamentum flavum from the skin, two points were positioned on the skin surface and the detected ligamentum flavum. The distance between the two points was measured by comparison to the distance measured by built-in MATLAB functions, which confirmed the same result.

The distance was adjusted according to the dots-per-inch (DPI) of each image. To increase compatibility with various manufacturers and different resolutions, the algorithms were designed to work with a range of DPI ultrasound images.

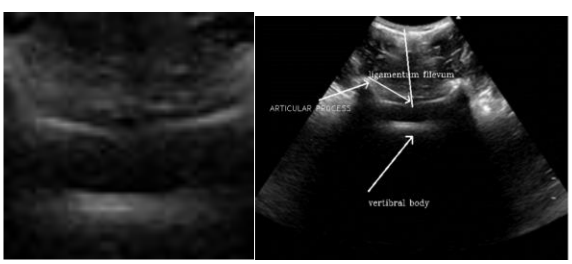

Fig. 4 (a) Template for matching. (b) Successful LF detection.

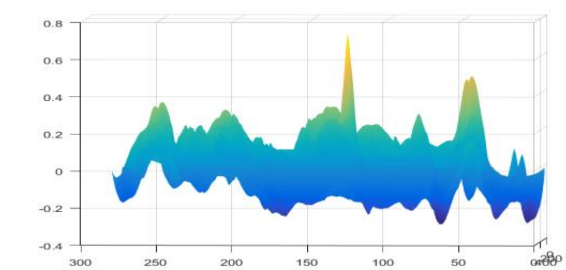

Fig. 5. Cross Correlation of template to detect LF.

(3) Identification of Spinous process (Midline)

Spinous processes were identified by two algorithms (1) ellipse detection (2) template matching, which were both tested on ultrasound images. We found that template matching was good for identification of spinous process (Fig. 6a). Ellipse detection sometimes had false positive detections of other ellipse shapes present in the image. False ellipse detection can be solved by adjusting the size of ellipses to detect (Fig. 6b). Template matching can fail in some images because of scaling, but to solve this problem we can load a greater number of template samples for various sizes.

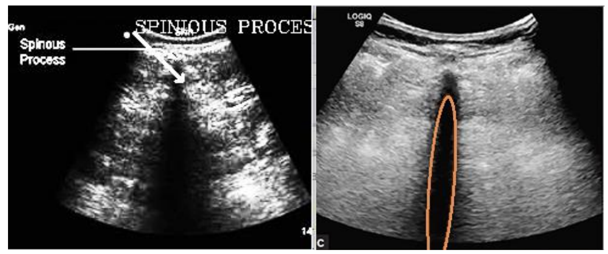

Fig. 6. Spinous process detected by (a) template matching, (b) ellipse detection.

4 Interpretation

In some cases, autonomous processing and interpretation of ultrasound is difficult, however if achieved, this will help since ultrasound is inexpensive and could be done online with portable systems that could improve safety of the procedure.

The developed algorithms are able to autonomously analyze ultrasound images by applying feature extraction and classification in real time. This can help the anaesthetist perform lumbar punctures including epidural anesthesia, by removing the task of manually monitoring the ultrasound and reduces potential risks of misinterpreting the ultrasound.

Our proposed methods for automating the analysis of ultrasound images could be developed on a tablet device which can wirelessly monitor the ultrasound data autonomously during a needle insertion. The proposed automated ultrasound will enable (i) observation of the conventional procedure providing alerts when required, or (ii) active guidance providing instructions on the direction and distance the needle should be moved in.

References

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