Deep Venous Thrombosis Screening System Using Numerical Measures

Julian Guerrero[1], S.E. Salcudean[1], James A. McEwen[1,2], Bassam A. Masri[2], Savvas Nicolaou[3]

[1]Department of Electrical & Computer Engineering, University of British Columbia, Vancouver, Canada
[2]Department of Orthopaedics, University of British Columbia, Vancouver, Canada
[3]Department of Radiology, Vancouver Hospital & Health Sciences Centre, Vancouver, Canada

Abstract—An experimental system and interface that indicate the likelihood of deep venous thrombosis using objective numerical measures was developed, based on the conventional compression ultrasound examination. A sensorized ultrasound probe is used to acquire force, location and image data to assess a vessel segment for compression. Ultrasound image data is segmented using a modified Star-Kalman algorithm. A user interface displays the results using a 3-D representation. A tissue phantom was developed for testing and validation. Initial results with this phantom and healthy volunteers are presented.

Keywords—Deep Venous Thrombosis, Ultrasound, Screening System.

I. INTRODUCTION

Deep venous thrombosis (DVT) is a well known disease that affects the circulatory system. The formation of thrombi in deep veins occurs because of sluggish blood flow or because of a hypercoagulable state. Thrombi may develop on vein walls occluding blood flow, or may break off and flow through the venous system to the lungs, causing a pulmonary embolism (PE) which may be fatal. Overall mortality of untreated DVT has been reported at approximately 2.5% [1].

The currently preferred screening method is compression ultrasound (CUS). A technician scans a patient using B-mode ultrasound to obtain transverse images of the patient's deep veins and by performing compression exams (compression-release cycles) at different locations to determine whether a thrombus is present in the patient's venous system by identifying incompressible vein segments.

CUS examinations rely on the expertise of the examiner [2]. Screenings may also take in excess of 40 minutes and in 76% of cases require repeat scans [1], increasing overall cost. Therefore, there is a need for a system that can objectively quantify thrombi and their location, through a single examination.

This paper presents our proposed system. A sensorized ultrasound probe is used to scan a vessel segment in order to determine the compressibility of that segment by computing two DVT indices. The acquired data is displayed in 3-D through a user interface in an intuitive manner. Preliminary results validating the system are also presented.

II. METHODOLOGY

The proposed screening system was developed based on the conventional CUS examination. In this procedure, a vein

is considered free of DVT when it is seen to completely collapse in the transverse plane when force is applied. Otherwise, it is possible that an intraluminal thrombus is present. A thrombus itself cannot be seen directly, since its echogenicity is similar to that of blood.

A complete CUS screening consists of scanning the deep veins every 2 to 5 cm from the common femoral vein near the groin down to the deep calf veins, to the extent possible. The results consist of stored 2-D ultrasound images showing compressed and uncompressed vessel segments, and a diagram schematically illustrating the location of thrombi if any were found.

In our system, compressibility of a vessel is determined by using a feature detection algorithm to identify the contour of a vessel in the transverse plane, while concurrent force and location measurements are taken. With this information, we can construct a transverse vessel area vs. applied force relationship for each examined vessel segment, generating an objective measure of the likelihood of DVT.

The characterization of clot compressibility for DVT detection using ultrasound elasticity imaging has previously been reported in [3], where ultrasound image speckle tracking and strain gauge information is used to determine the age of a thrombus.

A. Image Feature Detection

The detection of the transverse vessel contours is implemented using a modified Star-Kalman algorithm [4]. A circle was used in the original algorithm vessel model. This is not a suitable model for compressible veins. We assume that a vein contour is accurately described by an ellipse instead. The ellipse radius r is given by

$$r = ab \big/ \sqrt{b^2 \cos^2(\theta - \phi) + a^2 \sin^2(\theta - \phi)} \qquad (1)$$

where θ is the eccentric angle, ϕ is the angle of the semi-major axis a with respect to the image plane, and b is the semi-minor axis, as shown in Fig. 1(a). Both r and θ are measured from the center of the ellipse. It is assumed that the ellipse is centered at the origin of the coordinate system.

In the spatial domain we define a state vector $x_k = [r_k\ a_k\ b_k\ \phi_k]^T$ for each $\theta = 2\pi k / N$ from $k = 1$ to N, and write our system as

$$x_{k+1} = \begin{bmatrix} a_k b_k \big/ \sqrt{b_k^2 \cos^2(\theta_k - \phi_k) + a_k^2 \sin^2(\theta_k - \phi_k)} \\ a_k \\ b_k \\ \phi_k \end{bmatrix} + \xi_k \qquad (2)$$

and

$$v_k = r_k + \eta_k \qquad (3)$$

where r_k is the radial distance from the ellipse center to its edge along an angle θ_k (see Fig. 1(a)), a_k, b_k and ϕ_k are the estimates of a, b, and ϕ as defined in (1), v_k is the measurement vector, and ξ_k and η_k are system and measurement noise sequences, respectively, with known covariances.

An estimate of the state vector is generated by the modified Star-Kalman algorithm, through the well known implementation of an extended Kalman filter used for estimating parameters of a non-linear system [5]. The edge locations are described by the estimated r_k and the known values of θ_k for each k. Using the estimated ellipse parameters and (1) an ellipse is reconstructed. A data fit is deemed invalid if an error measure computed from the difference between the estimated points r_k and the generated ellipse is larger than a predetermined threshold.

An initial vessel location must be provided for the vessel center, which is subsequently tracked as in [4].

B. Location and Force Sensing

The force applied by the probe to the patient is measured by a sensor consisting of two rigid shells with a 6 DOF force-torque sensor (Nano25, ATI Industrial Automation, Inc.) between them, as shown in Figs. 1(b) and 1(c). The examiner grasps the outer shell and manipulates the probe in an ordinary fashion, while applied forces and torques are read into a computer.

A 6 DOF electromagnetic location sensor (PCIBird, Ascension Technology Corporation) is attached to the outer shell in order to obtain position and orientation readings. Many systems have used these types of sensors for tracking the location of ultrasound probes [6].

C. Compression Assessment Criteria

Two distinct measures are calculated from the acquired data and used to indicate the possibility of DVT for an examined vessel segment.

The first DVT likelihood measure is defined as the ratio of the minimum to the maximum transverse vessel area obtained at one vessel section and called the transverse area ratio (TAR). Values of the transverse vessel areas are approximated by the corresponding extracted ellipse parameters, since the ellipse area is $ab\pi$. Large values of the TAR indicate vein incompressibility and DVT.

The second DVT likelihood measure is obtained by fitting a line to the normalized measurements of area vs. force at the same location. A slope near zero indicates high likelihood of DVT while a slope close to -1 indicates low likelihood of DVT.
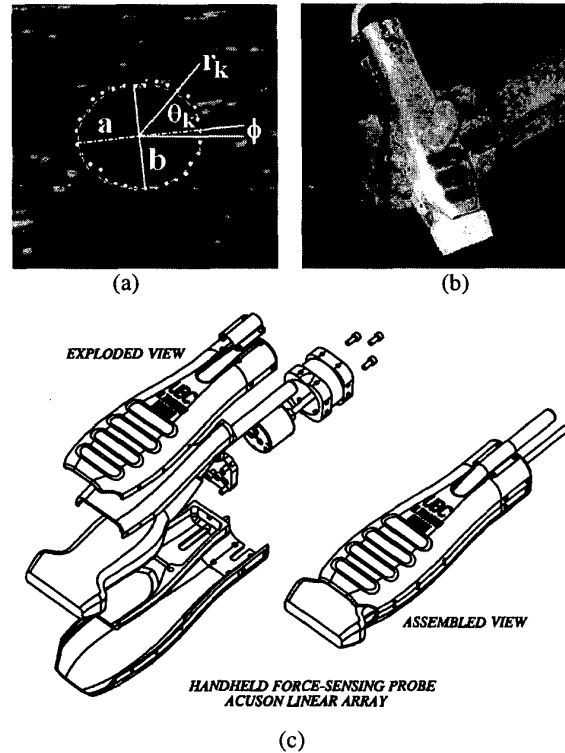

(a)   (b)

(c)

Fig. 1. (a) Ellipse model, (b) Ultrasound probe with shells used in DVT screening system, and (c) Diagram of ultrasound probe shells.

D. Data Display

A 3-D vessel model is constructed from the extracted vessel contours obtained under minimum force, which is displayed along with a virtual representation of the image plane with the current ultrasound image displayed on its surface. A conventional 2-D ultrasound image is also displayed alongside the virtual representation in the system interface, as shown in Fig. 2.

The compression information obtained for each vessel segment is mapped to the surface of the 3-D vein model using a range of colors. Therefore examiner can quickly identify from the display which vessel segments have been correctly screened for DVT and which were not, as well as the results of the screening.

E. System Integration

All ultrasound image data was acquired using a PC-based ultrasound machine (Ergosonix 500-RP, Ultrasonix Medical Corporation). All other sensor information was acquired using a second PC, which was connected by a LAN to the ultrasound machine. Image and data processing was performed on the second PC, which also displayed the user interface.

III. EXPERIMENTAL RESULTS

A. Feature Detection Results

In order to verify the ellipse parameter estimation, simulated ultrasound images with known elliptical features were generated using Field II© [7], similar to transverse images of a vein. The Star-Kalman estimation was performed on 300 images with a range of different initial conditions and different values for the ellipse parameters. The parameters a, b and ϕ, were estimated to within 4.03%, 7.81% and 1.79°, respectively, of the known values. The detected edge was also observed to correspond to the actual edge location. The computation time for each estimation is of the order of hundreds of milliseconds when implemented using Matlab© on a modern PC.

B. Validation of the Transverse Area Ratio (TAR) Criterion

The TAR criterion was initially validated with data from instructional videos [8] and videos of conventional compression examinations. While force measurements were not available for this validation, compression-release cycles were easily identified as well as the maximum and minimum transverse vessel area, making it possible to infer relative values of minimum and maximum applied force.

Examples of partially thrombosed veins ($n=3$) and of healthy veins ($n=10$) were identified. The 8 to 20 images for each case were segmented manually by the authors as well as by using the feature extraction algorithm presented herein. The average values for the TAR for healthy veins were 0.517% from the manually segmented data (M) and 12.959% from the extracted contour (E), while for diseased veins the values were 61.73% (M) and 59.63% (E). Figs. 3(a) and 3(b) show typical examples of normalized transverse areas of diseased and healthy veins and ellipse area computation.

C. Phantom Experiments

For developing and testing the system, a physical simulator or phantom was constructed using polyvinyl-alcohol (PVA) cryogel [9] vessels approximately 10 mm in diameter. These vessels were fixed within a Plexiglas container, and the interior of each vessel was accessible from the outside of the container. The tissue mimic surrounding the vessels was made using agar gel [10]. The vessels were then filled with water to represent a healthy vein or with a 12 mm x 4 mm cylindrical PVC thrombus mimic and water to represent a thrombosed vein.

The phantom vessels were scanned in a transverse plane. Compression-release cycles were performed at several locations, the data was processed, the TAR was computed, and the 3-D model of the vessel was constructed. Fig. 3(c) presents the TAR vs. phantom location for the `healthy' (H) and `diseased' (D) case.
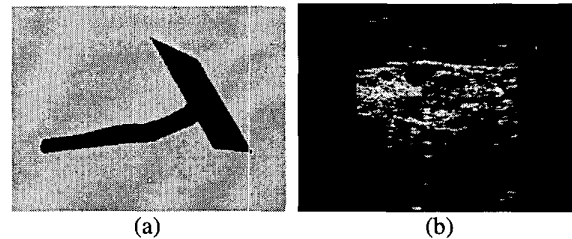

Fig. 2. DVT screening system interface, (a) Virtual vein model and image plane, (b) Conventional ultrasound B-mode image.

D. Healthy Subjects

Initial testing was performed on healthy volunteers ($n=3$), and several vessel segments were scanned in each case (total $n=10$). No diseased patients have been examined to date, but will be included for subsequent studies in order to properly validate our system.

Typical results of a compression exam on a superficial femoral vein using our system are presented in Figs. 3(e) and 3(f). The results show a line fit to the data with slopes near -1 and a small TAR values.

An arterial segment was also examined. The results for one compression-release cycle are presented in Fig. 3(d), and show a high TAR value and slope value near 0.

Invalid data due to a insufficient number of data points at a location was encountered in 15.9% of cases, due to insufficient force in 12.7% of cases, and due to outliers in 36.5% of cases ($n=63$ locations). This was due to inaccurate tracking because of the low frame-rate of our image acquisition from the ultrasound machine.

IV. DISCUSSION

The results obtained from testing the feature detection algorithm show that ellipse parameters can be identified reliably using the modified Star-Kalman algorithm over a range of conditions. The edge location was also detected accurately, and this performance was also seen when segmenting phantom and human images.

It is clearly evident that there is a large and consistent difference between healthy and diseased veins when comparing the respective TAR values. This validation suggests that the TAR is a useful measure for characterizing the possibility of DVT within a vessel.

The data obtained from the phantom and from human subjects also support the validity of the TAR criterion. The location of the thrombus phantom is clearly evident from the high TAR value for the example presented in Fig. 3(c). The human subject data presented in Figs. 3(e) and 3(f) clearly indicate the absence of DVT because of the low TAR value and slope value near -1, as expected. A high TAR value and slope value near 0 on the other hand indicate the incompressibility of an artery, as expected. The lack of
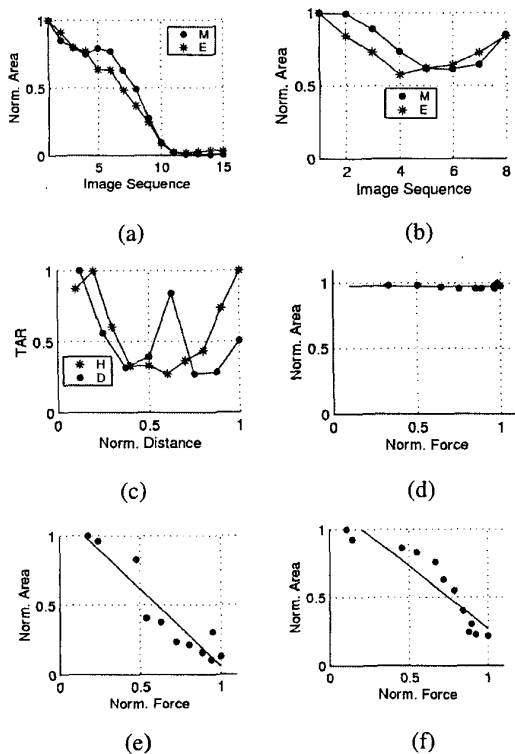
Fig. 3. Examples of transverse vessel area for (a) healthy and (b) diseased vessels, (c) Minimum transverse vessel area vs. location along vessel for phantom, and Compression examination data for (d) artery and (e,f) veins.

variation is expected from an incompressible vessel, and can be interpreted as a true positive result.

The authors are aware that the presence of metals has to be accounted for through calibration of the location sensor. Accuracy errors on known phantoms were found to be small enough not to interfere with the prototype demonstrated in this paper.

A. Future Work

There are still many possible improvements to the current system, and in depth testing to properly validate the system is necessary.

One drawback of the current feature detection algorithm is the inability to adequately detect a completely compressed vessel. This inadequate detection is the reason why the data indicates a larger average of the TAR for a healthy vein in Section III.B.

Low frame rate imposed limitations on the image tracking, and resulted in a large percentage of invalid data that would be acceptable in a clinical setting. Improvements to the system for better frame rate and image tracking

throughout an examination are necessary. It is expected that this will reduce the number of invalid datasets during a scan.

Extensive clinical and laboratory testing on healthy and diseased subjects is planned for validating the system. The phantom must be validated as well, by insuring that compression vs. area data and ultrasound images obtained from the phantom are consistent with data obtained from examinations of human subjects.

V. CONCLUSION

An experimental system and interface for the screening of DVT has been presented. The system uses automatic area computation, force sensing and sensor location to determine two numerical measures for the likelihood of DVT. These measures along with the sensor data are presented in a 3-D display to the examiner, as well as providing a record of the screening.

The system was evaluated on a custom made phantom as well as on healthy human subjects, with promising results.

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