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Automatic Estimation of the Optic Nerve Sheath Diameter from Ultrasound Images

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Abstract

We present an algorithm to automatically estimate the diameter of the optic nerve sheath from ocular ultrasound images. The optic nerve sheath diameter provides a proxy for measuring intracranial pressure, a life threatening condition frequently associated with head trauma. Early treatment of elevated intracranial pressures greatly improves outcomes and drastically reduces the mortality rate. We demonstrate that the proposed algorithm combined with a portable ultrasound device presents a viable path for early detection of elevated intracranial pressure in remote locations and without access to trained medical imaging experts.

1 Introduction

Portable ultrasound technology is well suited for the development of automated diagnostics systems that enable emergency responders to quickly assess the severity of a patient's injuries. Such light-weight portable automated systems can be employed in remote environments in which expert medical imaging personnel and advanced imaging equipment are not readily available.

This paper considers the application of a point-of-care, computer-assisted ultrasound system for in-field traumatic brain injury (TBI) assessment via the detection of increased intracranial pressure. Delayed treatment of increased intracranial pressure can cause temporary or permanent brain damage or even long-term coma and death. For example, it has been shown that acute subdural hematomas in severe TBI patients cause significant increase in intracranial pressure. Acute subdural hematomas are associated with 90% mortality if detected and treated more than 4 hours after injury, yet early treatment reduces the mortality rate to 30% [Se1981].

In a clinical setting, a non-invasive approach to measure intracranial pressure is by ocular ultrasound. From the ocular ultrasound image the physician manually measures the diameter

of optic nerve sheath at a location 3mm behind the retina. A diameter of the optic nerve greater than 5 mm indicates increased intracranial pressure [Ma2015]. Acquiring such images and making these measurements is a challenging and time consuming task. We propose to automate the process of measuring the diameter of the optic nerve sheath and integrate it with a portable ultrasound system to automatically report elevated intracranial pressure without the need of manually measuring the optic nerve sheath diameter. The ultimate goal is a system that is easy to use and does not require expert personnel or specific training to diagnose TBI.

Using ultrasound for estimation of optic nerve sheath diameter is a well establish approach to diagnose elevated intracranial pressure [Ki2008,Ro2011] and various studies have been performed to establish the optimal threshold for clinical diagnosis [Mo2009,Du2011,Ra2011]. However, to the best of our knowledge this is the first time an algorithm is proposed to automate the estimation process.

2 Algorithm

We propose a two step approach to automate the measurement of the optic nerve sheath diameter. At a high level, the algorithm proceeds by locating the eye through registration of an ellipse with the largest dark circle in the image data. From the ellipse an approximate location of the optic nerve is constructed and used to fit two bars to the walls of the acoustic shadow behind the optic nerve. This high-level description leaves out several intermediate image processing steps, described in detail in Section 2.1, that are required to achieve good registration results. Figure 1 shows result of the fitting procedure and illustrates that the proposed algorithm is applicable to a wide variety of ocular ultrasound images.

The algorithm is implemented in C++ and is available on github¹. The user-interface described in Section 2.2 is also available on github².

2.1 Algorithm Details

This section describes the individual image processing steps to achieve an algorithm that performs well on a large variety of images from different types of probes and differences between subjects.

The first part of the algorithm is locating and estimating the size of the eye. The liquid of the vitreous body of the eye has a very low acoustic impedance and appears as black ellipse in B-mode ultrasound images. The boundary of the vitreous body is frequently clearly delineated through the skin of the closed eye and the adjacent tissue. However, acoustic shadows, poor probe contact and collagen oaters cause imperfections in the boundary as well as the interior. Thus, the proposed eye detection algorithm requires several image processing steps illustrated in Figure 2.

In detail the steps are:

¹<https://github.com/KitwareMedical/UltrasoundOpticNerveEstimation>

²<https://github.com/KitwareMedical/UltrasoundIntersonApps>

1. Estimate initial eye center and size:
 - a. Gaussian smoothing, binary thresholding, morphological closing and distance transform.
 - b. The maximum distance provides the initial radius and the location of the maximum distance the initial center of the eye.
2. Refine initial estimates:
 - a. Distance transform over vertical image strip of width 20 pixels around the initial eye center location estimate provides an initial minor ellipse radius.
 - b. Distance transform over horizontal image strip of width 20 pixels around the initial eye center location estimate provides an initial major ellipse radius.
3. Gaussian smoothing and binary thresholding.
4. Create a binary ellipse annulus with the initial estimates of the minor and minor axis of width 0.2 times the major axis with center located at the initial eye center estimate.
5. Register ocular ultrasound (moving image) to ellipse image (fixed image) under an affine transform with a masked mean squared error metric. The mask is an ellipse that encompasses the ellipse annulus on the fixed image. The affine transform is centered on the ellipse center.
6. Refine eye center and major and minor estimates by applying the transform to the minor and major axis vectors and the center point.

The location of the eye provides an approximate region for locating the optic nerve sheath. The optic nerve sheath has a very strong acoustic impedance and reflects a significant amount of the energy of the ultrasound wave. This results in an acoustic shadow that appears as a darker tube behind the optic nerve sheath. We take advantage of this acoustic shadow to estimate the width of the optic nerve. The shadow boundary can exhibit several imperfections and have strong intensity variations. We propose several image processing steps, illustrated in Figure 3, to enhance the shadow boundary before a registration of two parallel vertical bars to delineate the width of the shadow.

In detail, the optic nerve sheath estimation steps are:

1. Extract optic nerve region below the eye using the eye location and size estimates
2. Gaussian smoothing.
3. Scaling of intensities per individual rows to alleviate attenuation effects.
4. Compute initial center and width estimates:
 - a. Binary threshold, morphological opening and distance transform.

- b. The maximal distance and its location provide an initial estimate of the optic nerve shadow diameter and its location
5. Scale intensities per row and on each side of the initial optic nerve center estimate independently (Often the left and right boundary exhibit vastly different intensities).
6. Refine initial center and width estimates:
 - a. Binary threshold, morphological opening and distance transform.
7. Use refined center and width to create an image with two vertical bars.
8. Register the two vertical bars (fixed image) to the processed image (moving image) under a similarity transform (rotation, translation and scaling) with a masked mean squared error metric. The mask is a rectangle that encompasses the two vertical bars. The similarity transform is centered on the initial center estimate.
9. Refine width estimates by applying the registration transform to a vector that spans from the left to the right vertical bar of the fixed image.

2.2 Interactive Graphical User Interface

The proposed algorithm is integrated into a user-friendly interface and performs for interactive estimation of the optic nerve sheath diameter. The GUI performs estimates at 4 frames per second, displays the registration results in near real-time and reports statistics of the estimates as they are acquired. Depending on the ultrasound probe, the algorithm can be simplified by skipping the eye estimation step to run at around 20 frames per second. The GUI can be used to report estimates of the optic nerve sheath diameter in near real time as an ultrasound probe is swept across the closed eye of a patient.

3 Evaluation

We evaluated the performance of the proposed automatic estimator in two ways. In Section 3.1 a comparison to manual estimates from novices and medical experts shows that the method has high precision and performs within the range of expert variability. Section 3.2 evaluates the automatic estimates using a gelatine eye phantom with known ground truth diameters and shows that the method is very accurate.

3.1 Comparison to Manual Estimation

For this study 13 volunteers ranging from novices to medical professionals annotated 23 ocular ultrasound images from the internet (in pixel units due to unknown image spacing units). Two linear regressions of the automatic estimates with two different parameter settings against the estimates of a medical expert resulted in an R^2 of 0.82 and 0.91, respectively. Both linear regressions were statistically significant with a p-value on the order of machine precision ($2e^{-16}$).

Table 1 contains all pairwise correlations between all participants of the study as well as two automatic estimates with different parameter settings.

Table 2 provides a summary of the pairwise correlations and reports the intra-and inter-correlation between novice, expert and automatic estimates. The estimates from the novice N1 were far off from any of the other novices and was excluded from the results reported in Tabel 2. The automatic estimates are more strongly correlated (0.85) to the medical expert than the correlation within the group of medical experts (0.81). The correlation among experts matches results of previous studies [Ze2014,Jo2016]. Thus, the proposed automatic estimator performs on par or even better than the medical experts.

3.2 Gel Phantom Study

This evaluation is based on an eye phantom using 3D-printed optic nerves (plastic discs) of known diameter embedded under gelatine orbs as described in detail in [Ze2014]. The eye phantom produces ultrasound images that closely resemble clinical ocular ultrasound images.

The goal of this evaluation is to check if an accurate estimate of the optic nerve is possible with the proposed algorithm. We imaged the phantom using the graphical user interface described in Section 2.2 connected to an Interson linear array probe with 127 transducer elements and a pixel resolution of 0.8 mm. A novice (non-medical imaging expert) used the graphical user-interface, which shows B-mode images in real-time, to first locate the optic nerve. Once the probe was positioned to deliver a good image of the optic nerve, as judged by the novice user, the automatic estimation process was started and run interactively for about 10 seconds. This resulted in approximately 40 to 50 optic nerve sheath diameter estimates.

Table 3 shows that, in this controlled setting, the means of the automatic estimates are within less than ± 5 mm and a relatively tight distribution of estimates around the ground truth diameter. The standard deviations of the individual measurements per disc are too large to accurately suggest elevated intracranial pressure. However, the mean deviation of the mean estimates from the ground truth over the 5 measurements is only 0.2 mm with a standard deviation of 0.18 mm. This suggest that the means reported by the automatic estimation procedure measurements are accurate enough to determine elevated intracranial pressure. In this small study the proposed algorithm yields more accurate results than reported in a study on intra-operator variations of manual estimates on the same type of phantom, but with higher resolution ultrasound probes, reports an average bias of 0.33 mm and standard deviations of 0.64 mm of the measurements [Jo2016].

4 Conclusion

The results presented indicate that the algorithm performs well in a controlled setting. A retrospective analysis of clinical images indicates that our system performs similar to an expert, and a phantom study using 3D printed optic nerves of known diameter suggests that our system is accurate.

The next step is to automatically identify high quality images as a probe is swept over the eye. This will eliminate the need for the operator to view, interpret, or make measurements on an ultrasound image when using it to assess a dilated optic nerve sheath. Ultimately, we aim for a system that can be used by novice operators with minimal ultrasound experience. The system will report when a sufficient number of high quality images have been acquired for an accurate estimate of the diameter. Based on this estimate it will be able to automatically indicate if the diameter of the optic nerve is greater than 5 mm and alert the user elevated intracranial pressure.

The long term goal is to develop a lightweight portable ultrasound system that, in addition to automated diagnosis of TBI, includes automatic diagnosis tools for pneumothorax (detached lung) and internal bleeding.

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References

- Dubourg, Julie, et al. Ultrasonography of optic nerve sheath diameter for detection of raised intracranial pressure: a systematic review and meta-analysis. *Intensive care medicine*. 2011; 37.7:1059–1068. [PubMed: 21505900]
- Johnson, Garrett GRJ., et al. Estimating the accuracy of optic nerve sheath diameter measurement using a pocket-sized, handheld ultrasound on a simulation model. *Critical Ultrasound Journal*. 2016; 8.1:18. [PubMed: 27832503]
- Kimberly, Heidi Harbison, et al. Correlation of optic nerve sheath diameter with direct measurement of intracranial pressure. *Academic Emergency Medicine*. 2008; 15.2:201–204. [PubMed: 18275454]
- Maissan IM, Dirven PJ, Haitsma IK, Hoeks SE, Gommers D, Stolker RJ. Ultrasonographic measured optic nerve sheath diameter as an accurate and quick monitor for changes in intracranial pressure. *J Neurosurg*. 2015; Sep123(3):7437.
- Moretti, Riccardo, et al. Reliability of optic nerve ultrasound for the evaluation of patients with spontaneous intracranial hemorrhage. *Neurocritical care*. 2009; 11.3:406. [PubMed: 19636971]
- Rajajee, Venkatakrishna, et al. Optic nerve ultrasound for the detection of raised intracranial pressure. *Neurocritical care*. 2011; 15.3:506–515. [PubMed: 21769456]
- Rosenberg, Jamie B., et al. Non-invasive methods of estimating intracranial pressure. *Neurocritical care*. 2011; 15.3:599–608. [PubMed: 21519957]
- Seelig, John M., et al. Traumatic acute subdural hematoma: major mortality reduction in comatose patients treated within four hours. *New England Journal of Medicine*. 1981; 304.25:1511–1518. [PubMed: 7231489]
- Zeiler FA, et al. A unique model for ONSD Part II: inter/intra-operator variability. *Can J Neurol Sci*. 41(2014):430–435.

Fig. 1.

Result of the proposed algorithm on three ocular ultrasound images. The overlays illustrate the registration results of the algorithm. The blue ellipse delineates the location of the eye and the red bars are the result of fitting the boundary of the acoustic shadow induced by the optic nerve sheath.

Fig. 2. Intermediate steps to locate and estimate the size of the eye. (a) Input image, (b) Gaussian smoothing and threshold, (c) distance transform, (d) the ellipse image generated from the initial eye location and size estimates and (e) the registered ellipse and optic nerve sheath overlaid on the input image.

Fig. 3.

Intermediate steps to fit the acoustic shadow of the optic nerve sheath. (a) Optic nerve sheath region extract based on the eye location and size estimates, (b) Gaussian smoothing and intensity scaling of individual rows, (c) Distance transform, (d) scaling of rows independently left and right of the initial center (e) thresholding and (f) vertical bars before registration based on initial estimates.

Fig. 4. The (a) GUI collecting estimates on an eye phantom in real time and (b) a close-up of the user interface. The GUI is running on a windows tablet connected to a USB linear array ultrasound probe from Interson.

Table 1

Pairwise Pearson's correlation coefficients between novice (N1 – N10), expert (E1 – E3) and automatic (A1, A2) estimates.

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	E1	E2	E3	A1	A2
N1	1	0.42	0.34	0.29	0.33	0.68	0.32	0.91	0.56	0.29	0.52	0.54	0.36	0.35	0.52
N2	0.42	1	0.83	0.93	0.92	0.85	0.95	0.56	0.83	0.93	0.86	0.91	0.95	0.91	0.89
N3	0.34	0.83	1	0.88	0.92	0.84	0.90	0.45	0.70	0.91	0.80	0.74	0.88	0.83	0.83
N4	0.29	0.93	0.88	1	0.94	0.80	0.96	0.42	0.74	0.97	0.82	0.83	0.94	0.92	0.85
N5	0.33	0.92	0.92	0.94	1	0.83	0.93	0.45	0.72	0.94	0.83	0.82	0.91	0.85	0.85
N6	0.68	0.85	0.84	0.80	0.83	1	0.83	0.75	0.79	0.82	0.83	0.84	0.83	0.83	0.86
N7	0.32	0.95	0.90	0.96	0.93	0.83	1	0.46	0.83	0.95	0.80	0.90	0.97	0.95	0.89
N8	0.91	0.56	0.45	0.42	0.45	0.75	0.46	1	0.60	0.45	0.60	0.66	0.51	0.51	0.63
N9	0.56	0.83	0.70	0.74	0.72	0.79	0.83	0.60	1	0.73	0.82	0.88	0.82	0.74	0.78
N10	0.29	0.93	0.91	0.97	0.94	0.82	0.95	0.45	0.73	1	0.85	0.80	0.94	0.91	0.84
E1	0.52	0.86	0.80	0.82	0.83	0.83	0.80	0.60	0.82	0.85	1	0.71	0.82	0.72	0.77
E2	0.54	0.91	0.74	0.83	0.82	0.84	0.90	0.66	0.88	0.80	0.71	1	0.90	0.88	0.87
E3	0.36	0.95	0.88	0.94	0.91	0.83	0.97	0.51	0.82	0.94	0.82	0.90	1	0.95	0.90
A1	0.35	0.91	0.83	0.92	0.85	0.83	0.95	0.51	0.74	0.91	0.72	0.88	0.95	1	0.92
A2	0.52	0.89	0.83	0.85	0.85	0.86	0.89	0.63	0.78	0.84	0.77	0.87	0.90	0.92	1

Table 2

Inter- and intra-correlations (mean Pearson correlation coefficients) among novice (excluding N1), expert and automated estimates.

	Novice	Expert	Automatic
Novice	0.78	0.83	0.82
Expert	0.83	0.81	0.85
Automatic	0.82	0.85	0.92

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Table 3

Automatic estimation results on eye phantom.

Disc Size	Mean	Std. Deviation	Low	Quartile	Median	Up.	Quartile
7mm	7mm	1mm	6.4mm	6.9mm	6.9mm	7.7mm	7.7mm
6mm	6.1mm	1mm	5.8mm	6.4mm	6.4mm	6.6mm	6.6mm
5mm	5.1mm	1.4mm	4.4mm	4.9mm	4.9mm	5.7mm	5.7mm
4mm	4.4mm	0.6mm	4.2mm	4.3mm	4.3mm	4.5mm	4.5mm
3mm	3.4mm	1.1mm	2.9mm	3.2mm	3.2mm	3.5mm	3.5mm