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ORIGINAL ARTICLE

Ultrasonic evaluation of pupillary light reflex

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Abstract
Background Evaluation of pupillary light reflex (PLR) is an important neurological test with a variety of clinical applications. Obstacles such as severe soft tissue damage or hyphema may obstruct the visual access to the pupil, thus rendering direct PLR observation difficult or impossible. Multipurpose ultrasonic systems, however, can overcome this problem.
Methods Using ultrasound imaging, a coronal view of the iris and pupil allowed visualization of PLR upon contralateral stimulation with a penlight. The technique was tested in ten healthy volunteers and a trauma case study.
Results Satisfactory visualization of the iris was achieved in all subjects, in an average time of 1 min 10 s. Temporal parameters of pupillary constriction, oscillations (hippos) and relaxation could also be measured on M-mode displays.
Conclusions Real-time coronal imaging of the iris using multipurpose ultrasound imaging is found to be a practical, fast and recordable method that can be used for evaluating PLR.

Keywords Iris · Pupillometry · Pupillary light reflex · Consensual pupillary reflex · Neurological trauma · Ultrasound imaging

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Introduction

The first ophthalmic ultrasound image was published in 1956 [1]. Since then, ultrasound imaging technologies have evolved to offer crucial diagnostic information in many ophthalmic conditions, such as complications of ocular trauma [2–5]. Ultrasound imaging is especially helpful when visual (optical) inspection is impossible to perform or does not provide a definitive diagnosis. Ultrasound in ophthalmology is employed in several clinical applications such as general-purpose ocular imaging (B-mode), ultrasound biometry that pursues precise distance measurements (A-mode), and ultrasound biomicroscopy (UBM) limited to the anterior segment, which uses high frequencies (e.g., 50 MHz) to provide a very high resolution of 33 µm and less [6–10]. Although very useful, specialized ophthalmic scanners or UBM devices are not available in the vast majority of emergency settings. Modern multipurpose ultrasound systems, on the other hand, are increasingly available for emergency imaging needs, and they have been demonstrated to provide excellent ophthalmic images when fitted with high-frequency probes [11]. Furthermore, high-end systems of this class employ sophisticated focusing, harmonic imaging and other optimization techniques that are not yet feasible in the "ophthalmic" ultrasound systems. In the absence of slit lamp capability or other imaging options, this imaging modality may seek to obtain information that is normally outside the generally recognized scope of ocular ultrasound.

The condition of the iris and its response to stimuli is of interest in a variety of conditions. Reviews on pupillary light reflex (PLR) and its clinical implications have been published [3, 12]. For example, absence of the PLR has been shown to be a risk factor independently associated with death in craniofacial trauma [13]. Prognostic consideration of pupillary diameter and constrictive ability was also recommended by the American Association of Neurological Surgeons [14]. Due to the importance of PLR evaluation, it seems prudent to consider other potential means of PLR assessment for instances when soft tissue damage, corneal opacity or hyphema may obstruct visual access to the pupil. Of the various pupillometry methods that have been described, the majority still require specialized hardware and expertise and are not available in the majority of emergency settings [15–17]. Multipurpose ultrasound imagers, however, are used in emergency settings worldwide, rapidly establishing a new role of sonography as a first-line modality for emergency departments at the patient's bedside [18–20]. These conventional multipurpose ultrasound scanners fitted with high-frequency probes in the 10–12 MHz range can be used to evaluate the condition of the globe and its components [21]. Taking advantage of the capabilities of these scanners, we developed a practical method to assess pupillary response to light.

The experiments described here have been part of a large ground-based study conducted by NASA to develop ultrasound imaging procedures for long-duration space flight. Since the only ultrasound device currently flown in space is a multi-purpose system (HDI-5000, ATL/Philips, Bothell, WA, USA), procedures and protocols were sought to take utmost advantage of the capability in the majority of foreseeable medical conditions in space, including ophthalmic trauma, blunt head injuries and body injuries, to name a few.

This work is based on the finding that besides antero-posterior planes, coronal or near-coronal sections of the eye are attainable, resolving the pupil in real time, clearly and separately from the strongly reflective lens (Fig. 1, Video 1). The ability to resolve the pupil using ultrasound allows for PLR evaluation. Consensual PLR, which is demonstrated in the procedure described, has been shown in human and animal experiments to be weaker, yet, is comparable to the direct PLR in terms of the degree of constriction [22–24]. Besides evaluation for instances such as neurological trauma, the method, with some modifications, may also be of interest for general ophthalmology and neurosurgery practice, as well as for research in neurophysiology, since it allows recording a variety of additional parameters such as rate of constriction, latency time, and dilatation time.

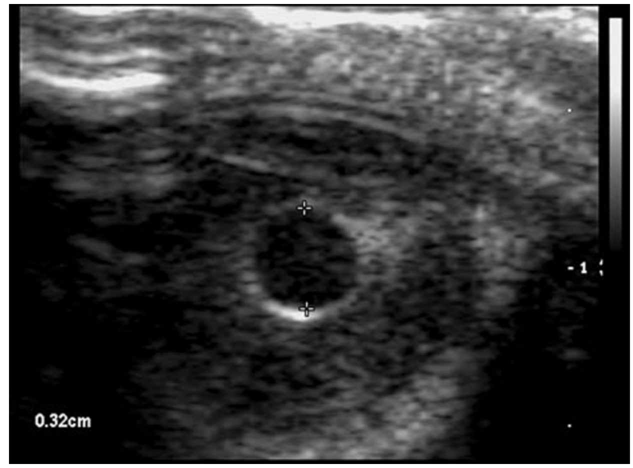

Fig. 1 Coronal view of the globe at the level of the iris. Measurements of the pupillary diameter are obtained using the measuring tool on the ultrasound system which displays the measurement in the bottom left corner

Materials and methods

A technique was developed for highly revealing real-time imaging of the entire iris and the pupil in coronal or near-coronal planes without lens interference. Multipurpose sonographic devices with high-frequency linear-array broadband probes were used. The specific systems used were an HDI-5000 multipurpose ultrasound system (ATL/Philips, USA) with a 5–12 MHz linear probe and a Sonosite-128 portable ultrasound system (Sonosite, USA) with a 5–10 MHz linear probe. Consensual PLR pattern was recorded as a series of coronal images of the iris. Corresponding M-mode graphs were also acquired to demonstrate the capability to plot the pupillary diameter versus time (Fig. 2). The technique was tested in ten healthy volunteers with various ocular and orbital topographies and also used in a trauma case study, in which all persons gave informed consent for their inclusion in this work. Imaging was performed through the skin and soft tissues, thus avoiding direct contact with the conjunctiva.

Imaging procedure

Following gel application on the probe face, the linear probe is placed below the orbit of the supine subject, strictly in a transverse plane on top of the zygomatic bone. Applying minimal pressure, the probe is then tilted about 45°

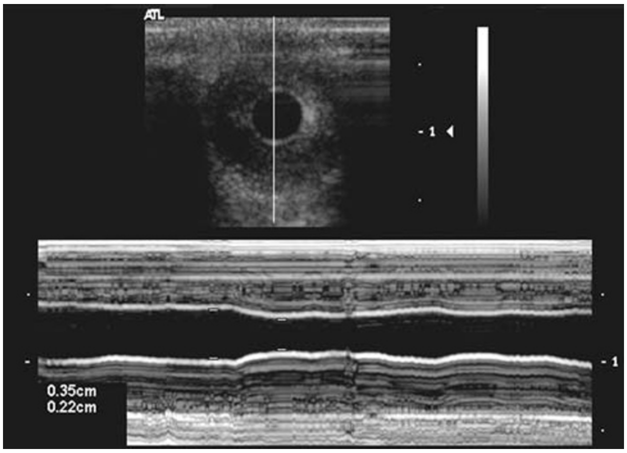

Fig. 2 Simultaneous B-mode and M-mode displays of consensual pupillary light reflex. The M-mode display shows the pupillary diameter as a black band straight across the bottom that displays the constriction of the pupil upon contralateral stimulation with a penlight

downwards, with the probe face pointing toward the orbit. With the other eye open, the subject is instructed to look at a fixed object on the ceiling, so that a stable gaze upwards is fixated. The probe is then carefully translated toward the orbit by 1–1.5 cm, just beyond the zygoma, enough for the probe to create a skin fold abutting the face of the probe (Fig. 3). "Traditional" sonographic orientation (left side of the screen corresponds to the subject's right side) is used. During translation, care is taken to avoid any substantial pressure on, and displacement of, the globe. Once an oblique section of the globe is clearly seen, the probe is slowly tilted further, to continue the transition of the scanning plane from the initial transverse plane to a near-coronal plane. Immediately after traversing the lens, the scanning plane is aligned with the plane of the iris, as shown in Fig. 4. Once the target image with the anechoic pupillary opening is achieved, consensual PLR is elicited by contralateral light stimulation with a penlight. The response can be documented in M-mode or by video recording of the ultrasound system's output (Video 1).

This technique can also be performed from a superior approach to the eye. Using this approach, the patient is instead instructed to look downward at a fixed object toward his or her feet. The probe is placed transversely on the superior margin of the orbit (frontal bone). With the probe facing toward the orbit, it is then tilted about 45° upwards until the iris and pupil are seen in full view. The consensual PLR can then be elicited as described above.

Case study

A 49-year-old male presented to the emergency department found unconscious by EMS after reportedly falling over ten feet from a ladder. The patient suffered extensive head trauma which caused elevated intracranial pressure and

Fig. 3 Probe placement is shown for acquisition of coronal images of the iris using a multi-purpose portable ultrasound system with a high-frequency linear probe

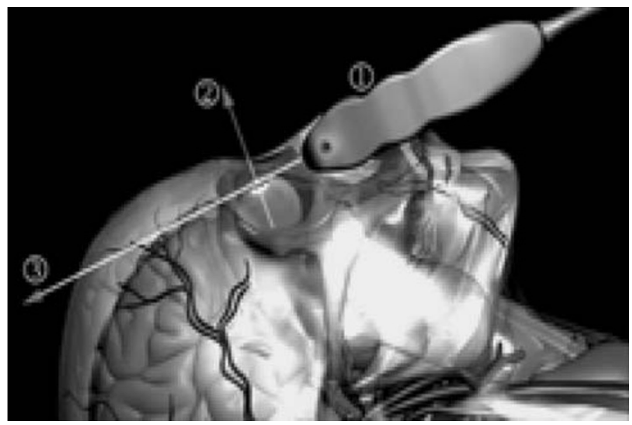

Fig. 4 The ultrasound scanning plane transects the globe in its coronal plane through the iris: *1* the ultrasound probe; *2* the direction of gaze; *3* the scanning plane (Courtesy of Butler Graphics, Inc.)

also, due to swelling and bruising, visual inspection of his eyes was difficult (Fig. 5a). In order to test PLR, sonography was used as described in the technique above. As seen in Fig. 5b, the probe was placed superior to the orbit and tilted upward until the iris and pupil could be seen in full view (Fig. 6). The PLR was visualized on the ultrasound display screen upon contralateral stimulation with a penlight. The technique proved to be a quick and practical tool in this case.

Results

Using the described procedure, coronal imaging of the iris was achieved in all subjects in less than 2 min with an average time of 1 min 10 s (range of 15 s–2 min). The discrete anechoic circle of the pupil surrounded by the typically patterned iris was clearly demonstrated in

Fig. 5 **a** Patient suffered substantial head trauma with swelling and bruising of the eyelids. **b** Ultrasound was used to evaluate PLR by placing the probe superior to the orbit to obtain a coronal view of the iris and pupil

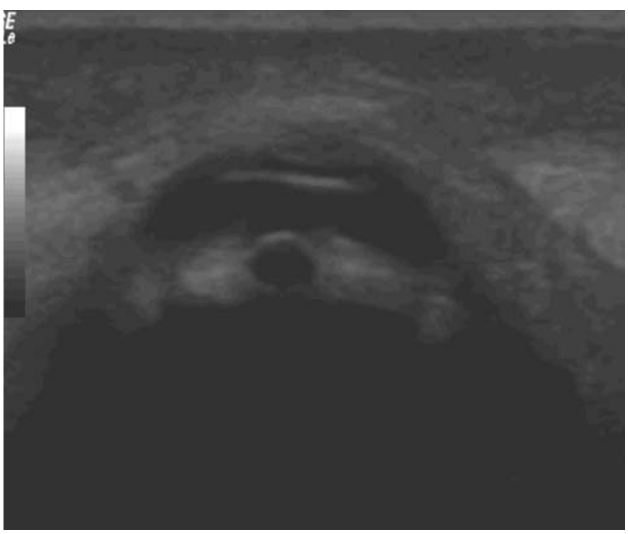

Fig. 6 Coronal image of the iris and pupil visualized with ultrasound in B-mode settings on the patient in the case study

the near-field of the live image (Figs. 1, 2). Thanks to the shallow situation of the target, optimal focusing and convenient zooming were possible, thus further enhancing the quality of the image. As shown in Fig. 1, the pupillary diameter is confidently measured and rounded to the second decimal of a centimeter (0.1 mm). Upon contralateral stimulation with a penlight, consensual PLR can easily be observed in real-time on the eye being examined (Video 1). Using M-mode settings, pupillary diameter can also be visualized over a period of time. On the M-mode strip, the superior-to-inferior diameter of the pupil was represented as a black band across the strip (Fig. 2). Temporal parameters of pupillary constriction, oscillations (called hippos) and relaxation could also be measured on M-mode displays.

The remarkable absence of lens interference is explained by the fact of the very acute incident angle of the ultrasound beam and near-ideally smooth and regular surface; thus, the lens does not produce any echoes that could return back to the probe. The iris, on the other hand, is an excellent scatterer due to its complex structure, surface and irregularities, comparable in size with the ultrasound wavelength in the soft tissues.

The temporal resolution in B-mode (grayscale), as determined by the actual frame refresh rate, could reach 10 ms depending on the image optimization used. M-mode temporal resolution can be substantially better if the 2D image remains "frozen" or is not displayed. In emergency settings, since the technique would be used to establish the presence or absence of PLR and therefore no measurements or M-mode recordings would be necessary, only the output of the ultrasound system would be recorded to document the results, if necessary. While the theoretical resolution at the frequencies used is 0.128 mm (12 MHz) or 0.154 mm (10 MHz), the actual accuracy is better with additional image optimization techniques available in these systems, such as high-definition zooming, image persistence, second harmonic imaging, and electronic focusing.

Conclusions

It has been shown that modern multipurpose ultrasound systems provide the capability of viewing and recording real-time grayscale images of the iris in coronal or near-coronal planes, with a clear, high-resolution view of the pupillary opening. Such imaging equipment, commonly found in a hospital's emergency department, could be used in a fast and practical manner for many clinical scenarios in which visual access to the pupil is hindered or rendered impossible. The dynamic nature of ultrasound imaging offers the possibility to measure and monitor the pupillary diameter and determine the presence or absence of consensual PLR, an important neurological test. This technique can also be used to record the pupillary diameter versus time, thus allowing analysis of the fine detail of the iris constriction, oscillations (hippos), or relaxation for both real-time and post examination. For this purpose, the M-mode capability of the ultrasound system is used. Other probes with slimmer design and higher (up to 15 MHz) frequencies may be more practical and convenient. Testing and application of the suggested procedure in the clinical setting seems to be a promising and valuable tool.

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Conflict of interest statement There is no conflict of interest related to the publication of this manuscript.

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