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MEDICAL OPHTHALMOLOGY

A novel eyelid motion monitor

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Abstract
Background Eyelid motion analysis can provide important information about ophthalmic, neurologic, and systemic diseases. Routine assessment of eyelid function is currently based mainly on clinical examination estimating Levator Function and static palpebral fissure measurements. Most clinical tools developed to date are cumbersome expensive and difficult to operate. Currently there is no widely available, affordable device providing user friendly precision based evaluation of eyelid kinematics. Our goal is to develop a novel device for evaluation of eyelid kinematics providing rapid defined diagnosis of diseases involving eyelid movement.
Methods A real-time prototype eyelid motion monitoring system was designed based on magnetic field sensors detecting movement of a tiny magnet located on the upper eyelid. Motion is recorded and analyzed using specially developed hardware and software, respectively, enabling both real-time and off-line data presentation. The Eyelid Motion Monitor correlates between blinking characteristics of eyelid movement and the output voltages produced by the system. Blink detection is defined as peak in voltage, caused by eyelid closure or opening. The device was tested on 20 healthy volunteers with normal clinical blinking patterns.
Results The Eyelid Motion Monitor succeeded in detecting full blink motion. The system easily extracts different parameters of eyelid kinetics.
Conclusions An inexpensive prototype novel device was developed for monitoring and analyzing eyelid motion characteristics, including the inter-blink interval, eye closing/opening duration and entire blink duration. The device should allow early objective non- invasive diagnosis and follow-up of disease progression. It could be of great potential value in many ophthalmic, neurologic, and systemic diseases.

Keywords Eyelid motion · Blink detection · Monitor device · Magnetic sensor

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Introduction

Ophthalmologists, neurologists, and general physicians examine the eyelids and their movements to assess and monitor many ocular and systemic diseases including Ptosis, Thyroid eye disease, Myasthenia Gravis, neurologic diseases such as third and seventh cranial nerve palsy and Parkinson's Disease [1–5]. A user friendly easily available monitor could potentially allow easier recognizable diagnosis and monitoring of disease such as blepharospasm, which is often missed in its early stage causing great suffering to the patient.

It could also be used potentially as a monitoring device to follow progression or regression of a disease such as thyroid-associated ophthalmopathy. Routine clinical measurement of eyelid status and movement is assessed using static metrics measuring levator and orbicularis muscle function. Many different techniques have been used to measure the time course of blinks, using coils, camera, electromyographic (EMG) recording, lever arm and photosensitive position detectors. High speed video recordings have also been used, which record the eyelid motion during downward and upward eyelid saccade [6]. However, to the best of our knowledge there is no readily available clinical device that allows user friendly evaluation of the kinematics of eyelid movements [7–9]. Most devices are cumbersome and are uncomfortable for the subject being examined, demanding the head stays in a fixed position on a chin rest so as it can be monitored. A device allowing free head position and movement should be far better and possible effects on eyelid blinking from fixed head position would be eliminated.

There are several measurable dimensions which characterize eyelid movement such as eye blink frequency, lid closing duration, eye closing/opening speed, i.e. the amount of time needed to fully close the eyes and to fully open them. In addition, measuring the amount of time the eyes are closed over the monitored period (the percentage of closed eyes over time) is also an important factor. The primary purpose of our apparatus is to monitor eyelid movements and to compute the relevant eyelid movement parameters. This paper focuses on the development of the Eyelid Motion Monitor (EMM) device, which records upper eyelid motion, in both eyes simultaneously and acquires vertical movement of the eyelids. This enables analysis and graphic presentation of the results. The device developed should allow the patient to move freely in his/her natural environment.

Methods

System description

The portable system developed consists of four components: (i) a tiny magnet (placed on the upper eyelid), (ii) glasses with magnetic field detectors for the patient, (iii) hardware - digital and analog cards that sample, process, store, or transmit the data managed by "eyelid device embedded software" and (iv) dedicated software allowing a user-friendly interface for the MD – "Eyelid Pro".

Tiny magnets attached to the upper eyelids generate varying magnetic field with the latter's movement. Four Hall Effect sensors, placed on an analog card attached to the glasses frame pick up the strength of the magnetic field at any particular moment. The magnetic field's strength depends on the position of the magnet in relation to the sensors. When a magnetic field is applied to the sensor, the latter returns a voltage that is determined by the strength of the magnetic field. Thus, if the system is calibrated properly, the voltage directly reflects the distance between the magnet on the moving eyelid and the sensor on the glasses frame. The magnet implanted on the upper eyelid generates a magnetic field (disk-type magnets, north-south pole orientation). The magnets used in the system are grade N50 Ni-Cu-Ni disk type magnets, with remanence of 1.825 T, weight of 34 mg, 3 mm diameter, and 0.65 mm height. Other magnets examined were found to be incompatible because of their impractical dimensions and weight on the eyelid or due to a weak undetectable magnetic field. The 34 mg magnet does not impair lid movement, causes no discomfort, and subjects become unaware of the magnet shortly after its application.

The system is equipped with two *analog* cards (one for each eye), each consisting of four Hall Effect probes placed strategically around the eye: above it (top sensors), below it (bottom sensors), between the eye and the nose ("internal" sensors), and opposite to them ("external" sensors). The probes' output voltage is pre-amplified and sent to the digital card, and each probe is assigned a number for digital processing (right eye probes are numbered 1–4, left eye probes are numbered 5–8), as seen in Fig. 1.

The *digital* card consists of a micro-processor and 2GB of data storage capability. The analog data is sampled at 400 Hz, which ensures that all physically possible frequencies will not be under-sampled. Two modes of operation are developed, online or offline. When online, the device is connected to a PC and the data is displayed instantaneously and stored on the Hard Drive. If offline, the data is stored in the internal memory of the device. At the end of the measurement, the data can be downloaded to the PC where the software may store, assist analyze, and present the data.

Eyelid Pro is a *National Instruments - Labview* based software that is aimed to supply the physician with a set of user-friendly and all-comprehensive tools to analyze, diagnose and document patients' eyelid movement. Eyelid Pro enables us to record eyelid motion, whether the EMM is connected directly to the computer during the measurement or used as a remote platform. *Eyelid Pro* uses a fast and reliable .CSV based data base in order to store the patient's personal information, recorded sessions data, doctor's remarks, and diagnostic results. The system software is user friendly for the physician, facilitating easy analysis of amplitude, velocity, rise and fall time, in addition to time duration between two blinks of each eye separately.

The theoretical signal

The signal contains many parameters of the motion, such as blink amplitude (position, symmetry), velocity, "opening" and "closing" duration (rise and fall time) of the blink, frequency between two adjacent blinks, and AVRB (Amplitude Velocity Ratio of Blinks). After adjusting the right topological configuration of the Hall-probes on the glasses, our goal is to establish the motion of the magnet from the voltage measurements by the four probes located on the analog card (numbered 1–4) while the eyelid's motion is in fact vertical (between probes 2 and 4). For example, when the magnet approaches the bottom sensor, its voltage rises until it peaks (indicating a fully shut eye), and upon moving away from this sensor, the voltage decreases until it peaks on a lower value (eye fully open). Figure 2 describes the predicted graph for each movement profile of the eyelid: closing, opening, and slow or fast full blink. The desired blink parameters are

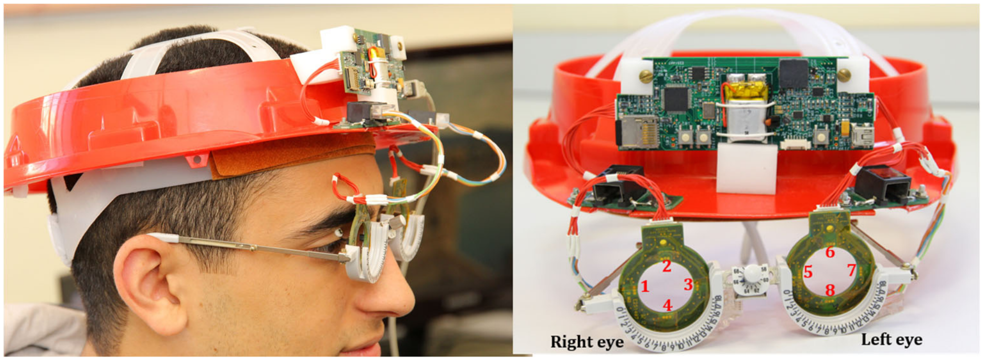


Fig. 1 Illustration of the Eyelid Motion Monitor device. *Left*: a subject while testing. *Right:*Glasses are equipped with two *analog* cards (one for each eye), each consisting of four Hall Effect probes placed strategically around the eye: above it (top sensors), below it (bottom sensors), between the eye and the nose ("internal" sensors) and opposite to them ("external" sensors). The probes' output voltage is pre-amplified and sent to the digital card, and each probe is assigned a number for digital processing (right eye probes are numbered 1–4, left eye probes are numbered 5–8)

extracted from the session's data, and compared to the blink shapes shown in Fig. 2. The main parameters of the signal are the duration of the blink, and the time between two consecutive blinks. The former is used to calculate the rise/fall time; the height of the pulse, which corresponds to the blink's amplitude, and the latter in order to find the blink frequency, as presented in Fig. 3.a.

Experiments

Two types of experiments were conducted to test the system's performance; (i) various types of blinks, as shown in Fig. 2, and (ii) clinical measurements in a natural environment.

In the first experiment, a magnet was placed on a patient's upper eyelid. The system was set up, prepared for measurement and calibrated to the patient. The patient was asked to perform three sets of blinks: four slow, five medium, and five fast blinks. The data was captured by the EMM device and transferred to the PC, for analysis.

In the second experiment, data was acquired from 20 healthy patients with no ocular or systemic disease. The subjects included in the study were recruited on a voluntary basis, and received a detailed explanation prior to the measurement. Control group: 20 healthy male and female subjects, with an age between 18 and 75.

The subjects' blinking pattern was monitored while viewing a movie under standard conditions: The patient sits 3 m from a 42 in. flat-screen TV, on a comfortable chair in a lighted room. A 6 min-long movie is viewed by the patient, while the device measures and stores eyelid movement data. After completion of signal acquisition, the data is transferred to a computer, where the dedicated "Eyelid Pro" software analyzes the results and displays them on screen for the doctor's review.

To ensure the integrity of the data, each patient was also filmed using a "GoPro" camera with high frame rate [10]. Prior to each session, the EMM and magnets were calibrated through the "Eyelid Pro" software in *online* mode. Each subject examined underwent "preliminary fitting" which involves performing a few sets of blinks to ensure that the magnets are equally placed with respect to the glasses. Following the "preliminary fitting", blinking data was recorded for 6 min with the EMM in *offline* mode, and later transferred to the PC for analysis.

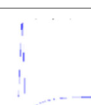
Movement Type	***Closing lids***	***Opening lids***	***Slow Blink***	***Fast Blink***
Predicted Graph				
Motion relative to the sensor	approaching	moving away	approaching and then moving away	

Fig. 2 Anticipated blink signal shapes during four different eyelid motion profiles, as measured by the bottom sensor. The x-axis represents time, and the y-axis represents voltage; when the magnet approaches the bottom sensor, its voltage rises until it peaks (indicating a fully shut eye), and upon moving away from this sensor, the voltage decreases until it peaks on a lower value (eye fully open). The signal shape also varies with slow or fast blink

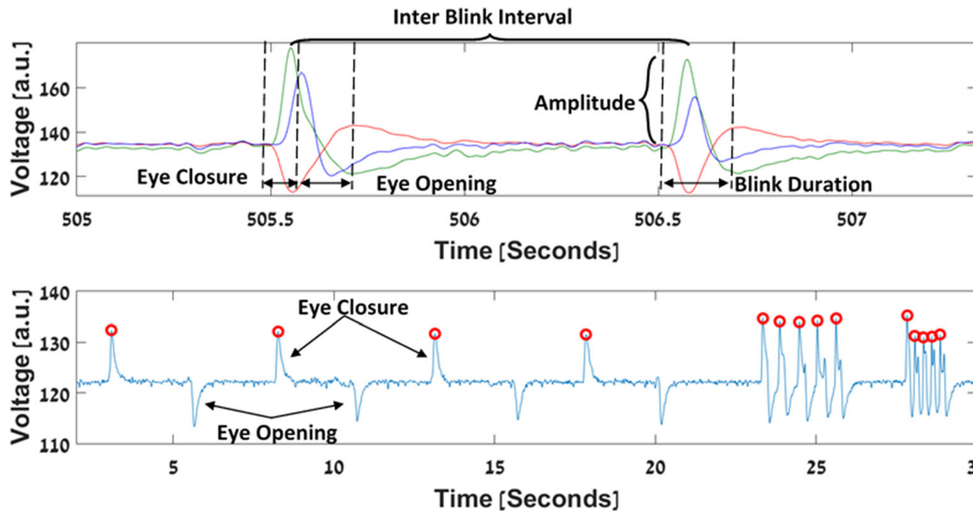


Fig. 3 (Top) An example of the raw data acquired by the upper (*red*)/ bottom (*blue*)/ side (*green*) sensors. The blink parameters: amplitude, blink duration, time between consecutive blinks, eyelid opening/closing are described on the graph. (Bottom) Data set acquired by the left eye's bottom sensor (#8): 4 slow blinks, 5 moderate, 5 fast. Detected blinks are marked in *red circles*

Results

In the first experiment, the three sets of blinks that the patient was requested to perform, are clearly distinguishable as shown in Fig. 3.b for data acquired by the bottom sensor. When the magnet moves away from this sensor, the voltage presents a negative peak, thus indicating the lid's opening. Conversely, when the magnet approaches this sensor, the voltage presents a positive peak, thus indicating the lid's closing. The software successfully detected all blinks (marked in red circles), determined the blink duration, and the time between consecutive blinks. For example, the average time between slow, medium, and fast blinks is 4.91, 0.571, and 0.261 s, respectively.

In the second experiment, the analysis of the 6-min data revealed that while the internal sensors have consistently proven to be the most accurate, there was repeated significant over-detection of blinks by the upper sensors and repeated moderate under-detection by the bottom sensors. This was a result of calibration problems, due to the incorrect positioning of the glasses, during the preparation for the measurement. Although we defined a setting in which the measurements should be repeatable and could be compared among different subjects, we encountered calibration problems due to large variability in the eye's structure between subjects. If the glasses sit too low, the bottom sensor does not sense the magnet when the eye shuts, therefore becomes ineffective. Moreover, since the upper sensor is too low in this scenario, the lid's opening and closing would result in the magnet *crossing* the sensor *twice*. Therefore, an over detection by the upper eyelid is anticipated—a phenomenon we next define as "horns".

Discussion

Eyelid movements and characteristics are often one of the first pathological changes visible of a systemic disease, and as a result clinicians such as ophthalmologists, neurologists, and endocrinologists dealing with issues find them of great interest. To date, no devices are used to diagnose routinely or follow up patients through monitoring of eyelid movement characteristics.

Most studies of eyelid kinetics to date have used cumbersome devices or methods demanding stable fixation of the examined subjects head on a chin rest in an unnatural position [1, 7]. This makes examination difficult and the fixation of the head also could theoretically cause changes in eyelid kinetics. Earlier studies used lever arm devices attached mechanically to the eyelid and a recording device including a pen, potentiometer, photosensitive position detector, moving light-emitting diode, and a search coil in a magnetic field. In addition, more recently methods using a search coil in a magnetic field technique and a charge-coupled device (CCD) camera, were published [1, 7, 11–17]. These studies can be challenging to perform in a regular clinical environment and are generally unavailable and expensive. In addition, most lack a mathematical model.

The EMM device which we developed is cheap, and easy to perform in the normal clinical set up, and could be produced easily as a readily available device for diagnosis and follow up. The net cost of building the monitoring system was approximately 450 Euro, thus a commercially manufactured model should not be very expensive. Magnets used were so tiny that subjects became unaware of them following their placement on the eyelid. There was no discomfort or problems with them during the monitoring examination in any subject examined.

The examination has no need for chin rests or head fixation and is performed in a normal environment without necessitating the use of any complicated or cumbersome devices. It provides a mathematical analysis of eyelid movement with a full detailed recording, through the dedicated software program. The entire examination, including setup, measurement and analysis of the results, is performed and completed within

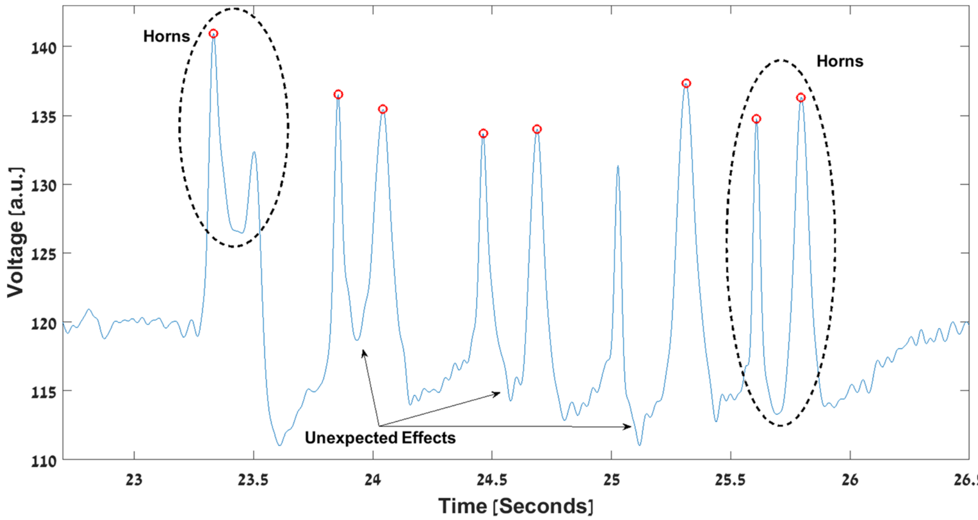


Fig. 4 "Horns" phenomenon from five consecutive medium-speed blinks, as acquired by the right eye's bottom sensor (#4). This phenomenon is the result of the device being positioned too high, and therefore, one blink is identified as two blinks

15 min. To date, no other method used seems to be able to provide comparable ease, simplicity, and rapidity.

Problems encountered when testing the device included misaligning of the device and background noise. Misaligning the device introduced a "horns" phenomenon as shown in Fig. 4, which presents five consequent blinks, as captured on the right eye's bottom sensor (sensor #4). As explained above, the positive peak in the bottom sensor corresponds to the lid's closing. This "horns" phenomenon may be helpful in future studies using magnetic fields to help calibrate the monitoring system properly.

The blinks in Fig. 4 were falsely detected as eight peaks instead of five, indicating that the magnet *crossed* the face of the bottom sensor twice, instead of simply approaching it. This is the result of the device being positioned too high. Thus, when the eye is shut, the magnet is undesirably positioned beneath the bottom sensor. As a result, when the eye shuts, the bottom sensor senses approach followed by undesired distancing, and then when the eye opens, the bottom sensor senses the magnet approaching (undesirably), and then distancing, instead of simply distancing. The undesired second approach, yields an unexpected second voltage peak, which forms the shape of "horns" together with the desired first voltage peak. Comparison to the session's filming asserted that the glasses were indeed positioned too high.

Although the measurements were sensitive to the glasses' position and the calibration process, we were able to solve the "horns" problem by introducing both hardware and software solutions. First, each sensor was bent towards the center of the eye to prevent the magnet from completely crossing the face of the sensor. Second, the blink extraction algorithm was improved to identify "horns" as single blink. The result of the same input as in Fig. 4, after applying the solution, can be seen in the second blink group of Fig. 3.b (medium-speed blinks), which also depicts "horns" yet only no false-detections. It is evidence that by applying the described solution, the system is capable of successfully detecting all the blinks and overcomes the "horns" calibration problems.

Regarding background noise and its separation from the sought-after parameters, we discovered another significant

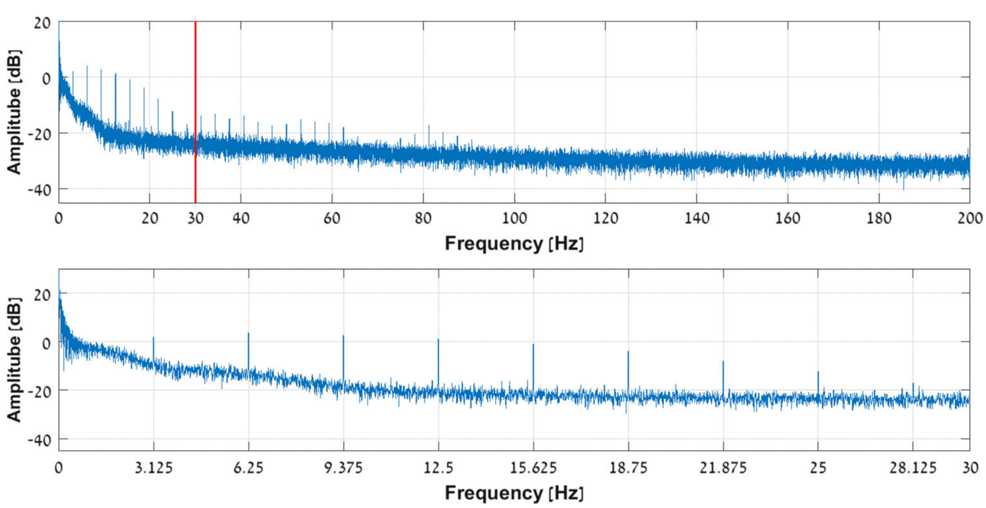


Fig. 5 (Top) Fourier analysis of the data acquired by the external left-eye sensor (#7). (Bottom) zoom in on the 3 Hz harmonics. The x-axis represents frequency, and the y-axis represents the amplitude of the blink

phenomenon. The measurements' spectrum frequency ("Fourier") shows that clinical diagnostic data are found only in frequencies below 30 Hz, see example in Fig. 5.a. We, therefore, filtered out noise above 30 Hz in order to both determine the clinical diagnostic data below 30 Hz, and in order to exclude the power grid frequency (50 Hz). This result is consistent with previous publications which determined the human frequency spectrum [18, 19].

However, we discovered peaks at ~3 Hz in the 30 Hz bandwidth and all its harmonics (multiplication possibilities such as 6, 9, 12, and so on) as shown in Fig. 5.b. We postulate that this energy is probably the frequency of eyelid arterial pumping as has been demonstrated in previous studies of arterial pulse in sheep, so that the phenomenon is not new [19]. Therefore, the EMM enables us to collect blink data, and in addition some undetermined phenomenon most likely related to arterial pulsation. Nevertheless, we will need to carry out a further study of this phenomenon and determine what specifically causes it.

Conclusions

We developed a new device which has potential to provide the medical community with a tool for recording and measuring eyelid motion. We believe that the system will enable us to diagnose and monitor many ocular and systemic diseases including chronic blepharospasm, ptosis, cranial nerve palsies, myasthenia gravis, thyroid eye disease, Parkinson's disease, and degenerative neurological diseases. Moreover, using this tool we should be able to determine the correlation between eyelid movements and other diseases which are not easily detectable presently.

The major advantages of the EMM device are its simplicity, robustness, and accuracy in addition to having the potential of being readily available and inexpensive. It is non-invasive, the set-up is simple, and it allows the patient to move about freely. The device was approved by the ethics committee and is currently being tested in the Ophthalmology Department of Emek Medical Center, Afula, Israel, in order to study the blink pattern of various diseases, such as blepharosphasem, Cogan lid twitch, Bienfang's sign, Marcus Gunn jaw winking.

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Compliance with ethical standards

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Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

Informed consent Informed consent was obtained from all individual participants included in the study.

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