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High-speed camera characterization of voluntary eye blinking kinematics

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Blinking is vital to maintain the integrity of the ocular surface and its characteristics such as blink duration and speed can vary significantly, depending on the health of the eyes. The blink is so rapid that special techniques are required to characterize it. In this study, a high-speed camera was used to record and characterize voluntary blinking. The blinking motion of 25 healthy volunteers was recorded at 600 frames per second. Master curves for the palpebral aperture and blinking speed were constructed using palpebral aperture versus time data taken from the high-speed camera recordings, which show that one blink can be divided into four phases; closing, closed, early opening and late opening. Analysis of data from the high-speed camera images was used to calculate the palpebral aperture, peak blinking speed, average blinking speed and duration of voluntary blinking and compare it with data generated by other methods previously used to evaluate voluntary blinking. The advantages of the high-speed camera method over the others are discussed, thereby supporting the high potential usefulness of the method in clinical research.

1. Introduction

A blink is defined as 'a temporary closure of both eyes, involving movements of the upper and lower eyelids' [1]. Human adults blink approximately 12 times per minute and one blink lasts about 1/3 s [2]. This natural eye motion is crucial for maintaining the integrity of the ocular surface for the following reasons: blinking (i) lubricates the eye by replenishing the precorneal tear-film, consequently preventing the cornea from dryness and cleaning the corneal surface, (ii) shields the eye from foreign objects such as dirt and dust as well as from the continuous exposure of light, and (iii) relieves early fatigue by allowing the ocular muscles in tension to be reorganized [1–3]. Three different forms of blinking have been described [1]; (i) spontaneous blink, which occurs unconsciously but periodically, (ii) voluntary blink, which occurs intentionally, and (iii) reflex blink, which is triggered by sudden impulse, loud sound or strong light. In this study, we consider voluntary blinks.

Blink characteristics, such as blink amplitude, duration and peak speed vary significantly between healthy and unhealthy eyes [4–7], and hence, an accurate and detailed analysis of a blink is important to detect debilitating conditions early and subsequently provide appropriate treatments. A few methods have been published as a way to investigate the rapid blink movements. The magnetic search coil technique involves taping a coil of copper or stainless steel onto a subject's upper eyelid then placing the subject in the centre of a weak magnetic field [7–10]. The eyelid position is then monitored by the current generated by the coil in proportion to the angle of the coil relative to the magnetic field, when the eyelid moves over the curved ocular surface. Other methods include home video camera recording [5,6] and tracking the displacement of a reflective marker taped onto a subject's upper eyelid using infrared cameras

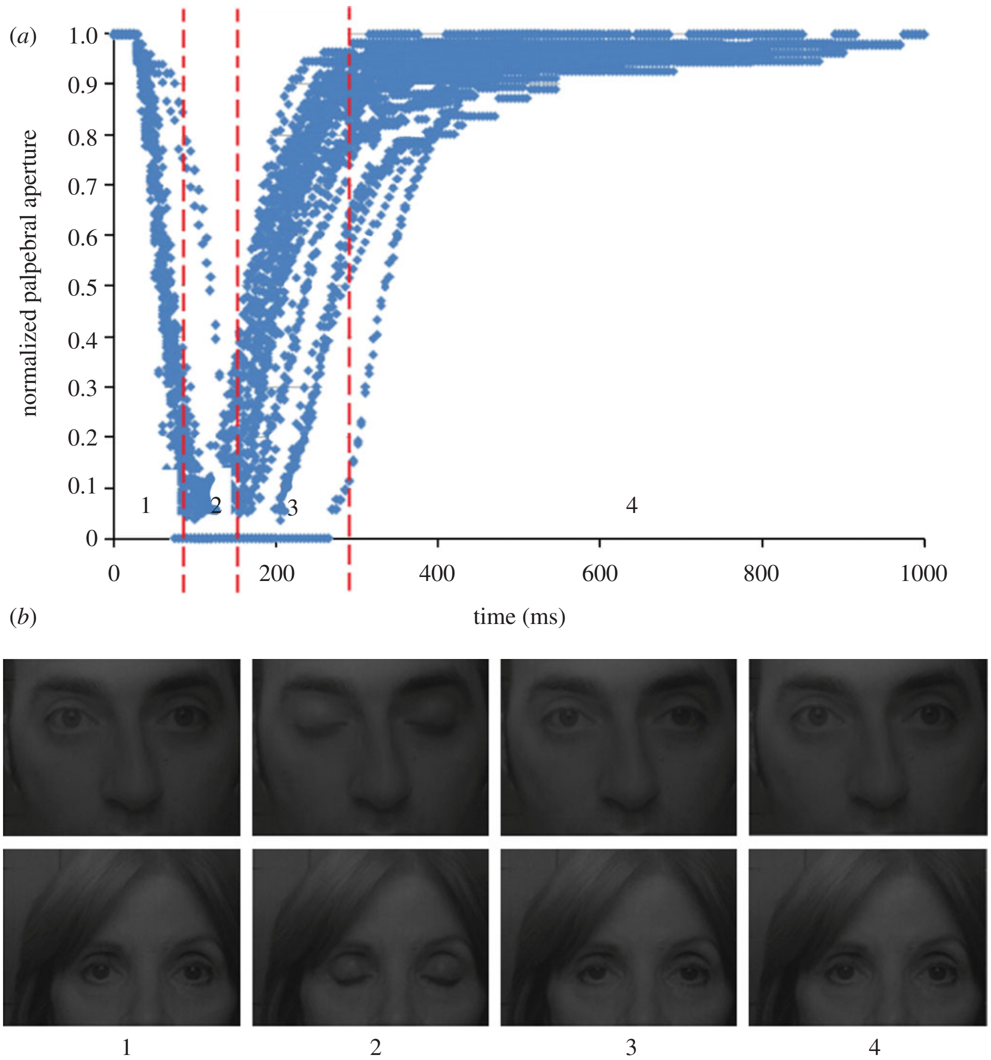

Figure 1. (*a*) Scatter plot of the normalized palpebral aperture for all 25 volunteers studied. (*b*) Key frame images illustrating each phase (these are also available on the electronic supplementary material, video). 1, 2, 3 and 4 refer to the closing phase, closed phase, early-opening phase, late-opening phase, respectively. (Online version in colour.)

[4]. In this work, a high-speed video camera was used to study the rapid eye motion of the voluntary blink. While most of the literature evaluates blink parameters such as blink duration and speed up to the point when about 97 per cent of the initial palpebral aperture is recovered; in this study, these parameters were evaluated for one complete blink, i.e. when the initial aperture was fully recovered. The results were compared with other reported values, exploring the potential use of the high-speed camera as an accurate and reliable analysing method.

2. Experimental details

Twenty-five healthy volunteers, including 11 males and 14 females participated in this study. Their age ranged from 25 to 63 with the mean of 35 years. Volunteers of oriental origin were excluded from the study. As this was a pilot study of 25 subjects, male and female volunteers were not considered separately. After informing the volunteers about the general purpose of this study, they were comfortably seated on a chair before a high-speed camera, one person at a time. A PHANTOM (v. 7.3, Vision Research Ltd, UK) camera was placed in front of the volunteers at their eye-level. The camera was mounted with a Nikon 24–85 mm F2.8 macro zoom lens and had 800×600 pixel resolution. In order to induce blinking, the volunteers were asked to blink as normal as possible after a verbal command. The motion of two voluntary blinks was recorded at a rate of 600 frames per second at 22.6 ± 1.6°C and 28.3 ± 2.2% humidity with natural light.

For each volunteer, the palpebral aperture, which is the vertical distance between the central points of the upper and lower eyelid margins, was measured every 5 ms of the recorded videos, using PHANTOM CINE VIEWER v. 2.14 (Vision Research software). The measurements started from 30 ms prior to the start of a downward movement of the upper eyelid and continued until the initial palpebral aperture value was reached. The second recorded blink was used for this analysis, considering the possibility that the volunteer was more comfortable and relaxed after the first blink. Since the initial palpebral aperture varied from one volunteer to another the measured aperture values for each volunteer were normalized and all the normalized aperture values for the 25 volunteers were averaged at each time point in order to produce a master curve for the palpebral aperture.

For each volunteer, the measured palpebral aperture values were plotted as a function of time and the corresponding blinking speed was determined by calculating the gradient on each consecutive pair of aperture points. When all the blinking speed values were determined for the 25 volunteers, they

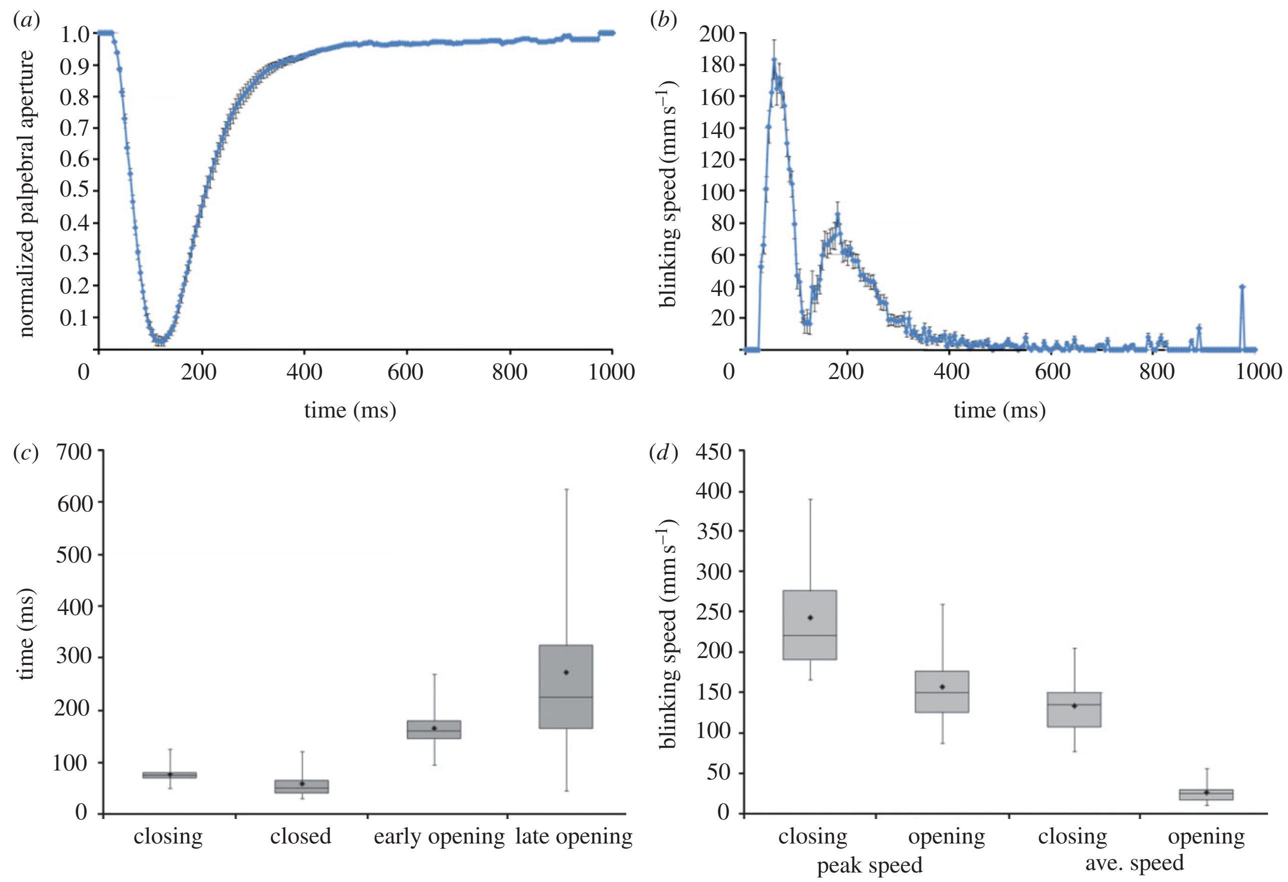

Figure 2. Master curve for (*a*) palpebral aperture and (*b*) blinking speed. (*c*) Box-plot of blinking duration for each phase and (*d*) box-plot of blinking speed for closing and opening phases. Each point on the curves represent mean $\pm$ s.d. and the diamond-shaped markers on the box-plots represent the mean values. (Online version in colour.)

were averaged at each time point in order to produce a master curve for blinking speed. The peak speed was taken to be the maximum speed calculated and the average speed was evaluated by dividing the initial palpebral aperture value by the time taken for closing the eye or opening the eye.

3. Results and discussion

The palpebral aperture measurements ranged from 7.4 to 12.8 mm with a mean of 9.8 ± 0.2 mm for all the 25 volunteers. These measurements agree well with Fox [11], who studied the palpebral fissure on 1732 human subjects using a millimetre-ruler and reported that the measurement varied from 7 to 13 mm with 61.7 per cent of the subjects having 9–10 mm aperture values.

All the normalized palpebral aperture values determined from the key frames of high-speed camera videos are shown in figure 1*a*. The aperture profile could be divided into four phases; (i) closing, (ii) closed, (iii) early opening, and (iv) late opening, depending on the action of the upper eyelid. Some of key frame images of the videos are selected to illustrate each phase (figure 1*b*). It is noteworthy that others [12,13] divide voluntary blinking into three phases: closing-phase, opening-phase and the inter-phase pause, i.e. the time elapsing between the end of the closing phase and the beginning of the opening phase. The inter-phase pause is important in clinical conditions, such as Parkinson's disease and atypical Parkinsonism.

During voluntary blinking, all the 25 volunteers fully closed their eyelids, thereby resulting in a brief closed phase with zero aperture values between closing and opening phases. Moreover, unlike the closing phase, the opening phase happened in two stages; early opening with continuous increase in palpebral aperture, corresponding to phase 3 and late opening with intermittent increase in aperture value, corresponding to phase 4. It was observed that about 97 per cent of the initial aperture value was recovered by the end of early opening, phase 3 and the last 3 per cent recovery during the late opening, phase 4. Averaging all the normalized palpebral aperture values and the speed values at each time point resulted in the aperture master curve (figure 2*a*) and the speed master curve (figure 2*b*), respectively.

The aperture master curve (figure 2*a*) shows how the aperture changed over time. It rapidly decreased until it reached approximately 0 for the first 110 ms, then increased rapidly but at a slower rate until 400 ms followed by a much slower increase until it reached its original value. Unlike in the normalized aperture scatter plot (figure 1*a*), the value never reached zero because of the variation in the timing and the duration of the closed phase between individuals. The speed master curve (figure 2*b*) exhibits two parabolic curves; one for the closing phase and the other one for the opening phase. The curve demonstrates that the upper eyelid accelerates until reaching its maximum speed then decelerates during the closing or opening action of the eye. The duration of one voluntary blink was determined for each phase (figure 2*c*).

The closed phase and the late-opening phase had the shortest and the longest duration with 58 ± 4 ms and 273 ± 23 ms, respectively. Moreover, a considerable variation was observed in the late-opening phase duration. Our video analysis showed that one voluntary blink took 572 ± 25 ms although only half

Table 1. Comparison of the parameters for a voluntary blink. The reported values are either mean ± s.d. or mean ± s.e., whereas our values are mean ± s.e.; amp, palpebral aperture; ave., average.

reference	year	method	number of individuals	age	closing phase amp (mm)	closing phase peak speed (mm s^{-1})	closing phase ave. speed (mm s^{-1})	closing phase duration (ms)	opening phase amp (mm)	opening phase peak speed (mm s^{-1})	opening phase ave. speed (mm s^{-1})	opening phase duration (ms)
[4]	2009	three infrared cameras (120 Hz sampling rate), following the displacement of a marker taped on the upper eyelid	10	65 ± 9	12.4 ± 0.7	340 ± 25		70.8 ± 4.3	12 ± 0.7	154 ± 11		168.5 ± 15.9
[5]	2003	home video camera (320 × 240 resolution; 60 fps sampling rate)	36	19 ~ 60 with ave. 31		154 ± 45	74 ± 22	125 ± 29		82 ± 21	39 ± 8	205 ± 32
[6]	2007	home video camera (640 × 480 resolution; 60 fps sampling rate)	72	16 ~ 76 with ave. 47.1		143 ± 60	52 ± 22	214 ± 59		83 ± 27	33 ± 12	321 ± 71
[7]	2006	magnetic search coil technique	14	43 ~ 75 with ave. 56.2	10.0 ± 1.1	285 ± 61		84 ± 13				203 ± 50
[9]	1997	electromagnetic search coil technique (500 Hz sampling rate)	8	40 ~ 49	11.7 ± 1.2	427 ± 30		71.1 ± 5.1	11.4 ± 1.1	165 ± 14		202.5 ± 13.3
			8	50 ~ 59	10.2 ± 1.4	329 ± 41		105.7 ± 13.8	9.9 ± 1.4	143 ± 18		233.5 ± 28.6
			8	60 ~ 69	10.6 ± 0.7	349 ± 25		83.1 ± 8.8	10.3 ± 0.7	145 ± 12		205.6 ± 8.9
this study	2013	phantom high-speed camera (800 × 600 resolution; 600 fps sampling rate)	25	25 ~ 63 with ave. 34.7 ± 1.1	9.83 ± 0.17	243 ± 9	134 ± 4	76 ± 2	9.83 ± 0.17	157 ± 5	26 ± 2	438 ± 24

of the time (299 ± 8 ms) was taken from the start of the blink to 97 per cent recovery of opening, i.e. from the closing to the early-opening phase. This result suggests that the very last half a millimetre of opening takes as much time as the time taken to reach up to that point. The peak and average speeds of blinking during the closing and opening action of eye are represented in figure 2*d*. The peak speed reached 243 ± 9 mm s^{-1} and 157 ± 5 mm s^{-1} during the closing and opening phase, respectively, whereas the average speed was 134 ± 4 mm s^{-1} and 26 ± 2 mm s^{-1}, respectively. These results suggest that a voluntary blink exhibits a temporal asymmetric pattern [2,8] with a much faster closing action than opening action. This difference in dynamics reflects differences in muscle fibre physiology between the orbicularis muscle, responsible for eyelid closure, and the levator palbebrae superioris (LPS) muscle, responsible for eye opening. The pretarsal orbicularis muscle consist of over 90 per cent fast-twitch type I fibres, in contrast to the LPS, which has a much lower proportion [14]. The blink parameters such as blinking duration and peak and average speeds determined in this study are compared with reported values (table 1). In general, the values obtained in this study were similar to the reported values apart from the opening-phase duration. While the opening-phase duration ranged from about 200 to 320 ms, it was measured to be about 440 ms in our study. This disparity might be due to the difference in how researchers defined the end of a voluntary blink or to the fact that these results were for a voluntary blink, which is greatly influenced by individuals as can be noted by the large variation in the reported duration of the closing phase, ranging from 70 to 215 ms.

Several reports have been published on employing a search coil technique to analyse blink motion [8–10]. However, this technique requires attaching fine wire coils of 2–6 mm in diameter onto a participant's upper eyelids as well as asking the participant to stay still in a weak magnetic field during the recording. Moreover, the coil marker has been reported to weigh from 20 to 160 mg, which might influence the blink kinematics and consequently the blink parameters. A high-speed camera does not require such devices, and hence it can be considered to be more convenient for both participants and researchers. Furthermore, the relatively high palpebral aperture measurements [4,9] may also reflect inaccuracies in measurement techniques that involve attaching either tape or coils to the upper eyelid, which may have only approximated the lid margin position. In contrast, more accurate and reliable results could be obtained from high-speed camera images as no extra eye weight, which might affect the blink dynamics, is involved and also the apparent palpebral aperture between the upper and lower eyelids is measured on a sequential series of images, whereas the coil marker is usually attached about 1 mm above the lid margin. The sequential series of images also mean more information can be retrieved, thereby allowing more detailed analysis of blink motion. These benefits of high-speed camera imaging over a search coil can make it a more attractive method to analyse eye blinking kinematics.

4. Conclusions

The kinematics of one voluntary eye blink was studied using a high-speed video camera recording at 600 frames per second. The analysis of data recorded showed that one voluntary blink could be divided into four phases; closing phase, closed phase, early-opening phase and late-opening phase identified by the distinctive action of the upper eyelid. One blink took 572 ± 25 ms and was accompanied by asymmetric motion with a much faster closing action compared with the opening action of the eye. The peak speed was determined to be approximately 250 mm s^{-1} and 160 mm s^{-1} during the closing and opening phases, respectively, and the closed phase and the late-opening phase took the shortest and longest time, respectively. Comparing the results in this study with other reported findings demonstrates that the high-speed camera technique provides highly reliable results and its advantages over the other techniques can make it a more attractive method to investigate the kinematics of a human blink. This methodology has significant implications for clinical research and practice, providing an experimental platform to examine abnormalities of eyelid movement, such as blepharospasm, thyroid eye disease and myopathic ptosis.

A further study is on-going with a higher number of volunteers to allow for the correlation of blink characteristics with age, gender and other clinical variables. In addition, investigations comparing blink dynamics of healthy and disease states are also on-going.

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References

1. Blount WP. 1927 Studies of the movements of the eyelids of animals: blinking. *Exp. Physiol.* **18**, 111–125.
2. Fatt I, Weissman BA. 1992 *Physiology of the eye: an introduction to the vegetative functions*, 2nd edn. Boston, MA: Butterworth-Heinemann, a division of Reed Publishing (USA) Inc.
3. Doane MG. 1980 Interaction of eyelids and tears in corneal wetting and the dynamics of the normal human eyeblink. *Am. J. Ophthalmol.* **89**, 507–516.
4. Bologna M, Agostino R, Gregori B, Belvisi D, Ottaviani D, Colosimo C, Fabbrini G, Berardelli A. 2009 Voluntary, spontaneous and reflex blinking in patients with clinically probable progressive supranuclear palsy. *Brain* **132**, 502–510. (doi:10.1093/brain/awn317)
5. Choi SH, Park KS, Sung M-W, Kim KH. 2003 Dynamic and quantitative evaluation of eyelid motion using image analysis. *Med. Biol. Eng. Comput.* **41**, 146–150. (doi:10.1007/BF02344882)
6. Choi SH, Yoon TH, Lee KS, Ahn JH, Chung JW. 2007 Blepharokymographic analysis of eyelid motion in Bell's palsy. *Laryngoscope* **117**,

308–312. (doi:10.1097/01.mlg.0000250775.13390.49)

7. Korošec M, Zidar I, Reits D, Evinger C, VanderWerf F. 2006 Eyelid movements during blinking in patients with Parkinson's disease. *Mov. Disord.* **21**, 1248–1251. (doi:10.1002/mds.20930)
8. Evinger C, Manning KA, Sibony PA. 1991 Eyelid movements: mechanisms and normal data. *Invest. Ophthalmol. Vis. Sci.* **32**, 387–400.
9. Sun WS, Barker RS, Chuke JC, Rouholiman BR, Hasan SA, Gaza W, Stava MW, Porter JD. 1997 Age-related changes in human blinks. *Invest. Ophthalmol. Vis. Sci.* **38**, 92–99.
10. VanderWerf F, Brassinga P, Reits D, Aramideh M, de Visser BO. 2003 Eyelid movements: behavioral studies of blinking in humans under different stimulus conditions. *J. Neurophysiol.* **89**, 2784–2796. (doi:10.1152/jn.00557.2002)
11. Fox SA. 1966 The palpebral fissure. *Am. J. Ophthalmol.* **62**, 73–78.
12. Bologna M, Fabbrini G, Marsili L, Defazio G, Thompson PD, Berardelli A. 2012 Review: facial bradykinesia. *J. Neurol. Neurosurg. Psychiatry*. (doi:10.1136/jnnp-2012-303993)
13. Bologna M, Fasano A, Modugno N, Fabbrini G, Berardelli A. 2012 Effects of subthalamic nucleus deep brain stimulation and L-DOPA on blinking in Parkinson's disease. *Exp. Neurol.* **235**, 265–272. (doi:10.1016/j.expneurol.2012.02.004)
14. Ezra DG, Beaconsfield M, Collin R. 2009 Surgical anatomy of the upper eyelid: old controversies, new concepts. *Expert Rev. Ophthalmol.* **4**, 47–57. (doi:10.1586/17469899.4.1.47)