Special Issue

Functional Visual Acuity

Minako Kaido

Department of Ophthalmology, Keio University School of Medicine, Tokyo, Japan

Correspondence: Minako Kaido, Department of Ophthalmology, Keio University School of Medicine, 35 Shinanomachi, Shinjuku-ku, Tokyo 160-8582, Japan; fwiw1193@mb.infoweb.ne.jp.

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Dry eye (DE) causes irregularity of the ocular surface and reduces the quality of vision. An intact, regular tear film is essential for high-quality retinal images; however, visual tasks requiring sustained gazing can disrupt the tear film, eventually degrading visual function. A functional visual acuity (FVA) measurement system has been uniquely developed in Japan to evaluate visual function related to tear stability in patients with DE. FVA has been shown to correlate with optical quality. The system measures the change in visual acuity (VA) over time automatically in aqueous-deficient DE and short tear breakup tear film DE characterized by decreased tear stability and minimal epithelial damage. It is also useful to detect minimal visual deterioration correlated with minimal ocular surface abnormality and vision-related quality of life otherwise undetectable by conventional VA testing, to assess and quantify vision-related symptomatology, and to determine the efficacy of treatments for DE disease. Recently, its use has been expanded, such as for the analysis of visual function accompanying refractive surgery, contact lens, cataract and cataract-related disease, retinal disease, glaucoma, amblyopia, presbyopia, and vehicle driving. Its use has revealed that FVA reflects not only visual function related to tear dynamics, but also visual function related to quick recognition of the target. This simple, noninvasive, and sensitive FVA measurement system may be expected to be used worldwide.

Keywords: dry eye, functional visual acuity, tear film, visual function, tear breakup time

Vision is an essential part of everyday life. With the advances in the ophthalmologic field in the past decades, the purpose of treatment is no longer limited to preventing a reduction of vision, but to obtain better quality of vision. Dry eye (DE) is one of the most frequently encountered ocular morbidities in the context of recent environmental and lifestyle changes brought about by excessive visual display terminal (VDT) use, contact lens wearing, and aging.[1–8] Recent studies have established a relationship between visual impairment and ocular surface irregularity in DE.[9–17] There are several measurement methods for visual quality. Subjective methods include special visual acuity (VA) and contrast sensitivity testing; and objective methods include ocular wavefront aberration analysis, scattering device testing, and tear stability analysis.[18]

The functional VA (FVA) measurement system is a unique method developed in Japan. The system measures the change of VA over time. It allows the detection of impaired visual function related to tear stability in patients with DE, which cannot be detected by conventional VA testing.[19–21] This article reviews the details of the FVA measurement system.

Concept of FVA

FVA represents the visual function in consideration of the time axis. The concept comes from the experiences of blurred vision and/or eye fatigue during driving, reading, or working at VDT tasks.

Tear film, the most anterior refractive surface of the eye, is a critically important factor contributing to stability of the ocular optical quality.[13,14,16,22–24] An intact and regular tear film is essential for high-quality retinal images; therefore, a deteriorated tear film can degrade visual function. Visual tasks requiring sustained gazing may reduce the number of eye blinks, which play an important role in lubricating the ocular surface. Thus, it may induce a temporary reduction in visual function due to the disruption of ocular surface smoothness. Its impact is even larger in DE than in non-DE disease. The advantage of the FVA measurement system is that it can detect impaired visual function in visual tasks of daily life.

Recent Progress Around the World

Besides the FVA measurement system, several other special VA tests are available that measure VA over time. The Interblink Interval Visual Acuity Decay (IVAD) is a test that evaluates functional VA between blinks. It is a computer-based system that presents the optotype Landolt C at the patient's best-corrected VA, and then VA decay results are measured in milliseconds. During the test, the rotating optotype "c" is presented. The patient is instructed to track the orientation of the C by pressing a button on a keypad. During the patient's interblink interval, his or her best-corrected VA declines as the size of the stimuli decreases. By measuring the time to maintain the highest VA in between blinks, visual function is assessed as visual task performance in real time. Walker et al.[25] demonstrated the diurnal variation of impaired visual function in DE using this IVAD test. The sentence-based and/or paragraph-based reading test is another evaluation method for visual function. Speed to read words and/or sentences written in characters with and without contrast is evaluated as a visual function parameter. Ridder et al.[26] and Ousler et al.[27] showed the reduction of reading ability in DE compared with non-DE, demonstrating the relevance of a measurable assessment of visual function in DE. Ridder et al.[26] also showed that DE severity is correlated with the reading rate.

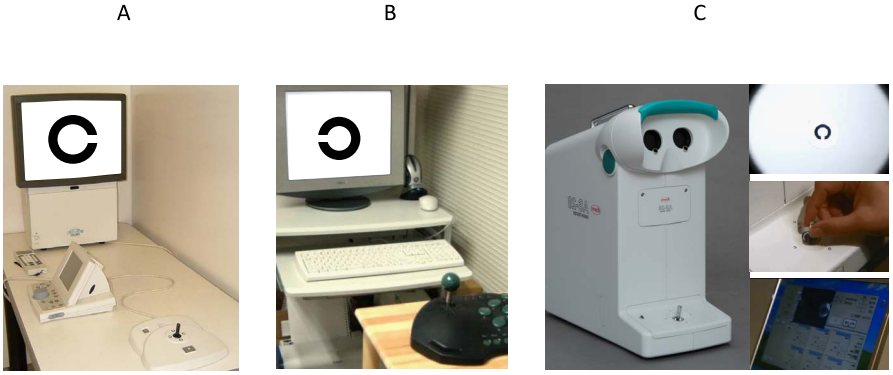

FIGURE 1. FVA measurement system. (**A**) First model. (**B**) Second model. (**C**) Current model.

RECENT PROGRESS IN JAPAN

The FVA measurement system has made progress in the past 20 years. Goto et al.[28] first defined the FVA as visual function of daily acts of gazing. It was measured manually with sustained eye opening for 10 to 20 seconds with topical anesthesia, to simulate the situations when blinking is suppressed during reading, driving, or working at visual terminals. This measurement method is affordable without requiring special equipment and thus easily applicable in clinical practice; however, the measurements may depend on the ability of the measurer to obtain high repeatability and reliability. To cope with the manual measurement, a new FVA measurement system has been developed to examine the change in VA over time automatically.[29] The system comprises the instrument body, a monitor displaying an optotype, and a joystick for responses (Fig. 1A). The first model had a system in which the displayed optotype increased by one size when the response was incorrect, and it remained unchanged when the response was correct. This specification was based on the concept that VA should be reduced but not restored over time, as the tear-film layer becomes irregular due to dryness by eye opening with blinking suppression. The upgraded model (SSC-350; Nidek, Gamagori, Japan; Fig. 1B) provided two improvements. One is that a new useful parameter, visual maintenance ratio (VMR), was applied to evaluate the difference between FVA and starting VA (i.e., best-corrected VA).[30] With this parameter, statistical comparison of FVA between patients with different best-corrected VAs became possible. The other is that the display system of optotypes was improved. Namely, the displayed optotype is increased by one size when the response is incorrect and decreased by one size when the answer is correct twice in a row. This improvement was made to respond to unintentional mistakes and to evaluate visual performance more accurately. From this time, FVA became measured with natural blinking. It is based on the evidence that FVA measured under natural blinks reflects the tear functions and ocular surface status rather than the measurement under blinking suppression.[31] Blinks are recorded only manually when an examiner taps a keyboard while observing the patient's blinking. The latest model of the FVA measurement system, AS-28 (Kowa, Aichi, Japan; Fig. 1C), is a peeping-type equipment with automatic blink recognizing function. With previous models of the FVA measurement system, the examination was performed at a distance of 5.0, 2.5, or 1.0 m depending on the patients' best-corrected VA. However, the latest model is compact and does not need a space for the measurement distance. Optotypes of decimal VAs from 0.1 to 1.5 can be measured. In addition, automatic measurement of blinks became possible. The sensor recognizes a blink when blinking occurs beyond the central cornea.

Measurement Method

Before use, the FVA system is required to be set up: the measurement time, which can be selected from 1 up to 60 seconds, is generally set in 60 seconds; and the optotype display time, which can be selected from 1 to 5 seconds, is generally set in 2 seconds. In the setting of display time to 2 seconds, the patient is required to respond in less than 2 seconds. No response within 2 seconds is regarded as incorrect. The optotype is increased by one size automatically when the response is incorrect or when there is no response. An optotype of the same size is displayed at random again when the response is correct. The optotype is decreased by one size when the next answer is correct (Fig. 2).

The FVA testing is generally performed under full refractive correction and spontaneous blinking without topical anesthesia. The test begins with the best-corrected Landolt VA, which is the baseline VA. Patients delineate the orientation of the automatically presented Landolt ring on the built-in screen in the peeping-type equipment by handling the joystick from the baseline VA from the start. After a preliminary test in the practice mode of 15 seconds, the actual test is conducted. The results are recorded as a list of timewise VA with decimal notations and logMAR conversion. The continuous VA change is plotted in a graph (Fig. 3).

Evaluation Index

Evaluation indices are starting VA, FVA, VMR, maximal and minimal VA, average response time, and blink frequency. Starting VA is defined as the baseline VA, which is the value of the standard best-corrected VA measured by the FVA system. FVA is defined as the mean value of timewise change of the VA during the overall examination. The VMR is the ratio of FVA divided by the value of baseline VA, calculated as follows: VMR = (lowest logMAR VA score − logMAR FVA) / (lowest logMAR VA score − baseline logMAR VA). The lowest logMAR VA score is defined as 2.7.[30] The maximal and minimal VAs are defined as the highest and lowest VAs recorded during the examination. Blinks measured automatically are marked exactly when blinking.

Application of the Measurement System for Screening of DE

The possibility of the FVA measurement as a screening tool of DE has been suggested. We conducted a study to investigate whether FVA examination can discriminate patients with DE from most VDT users, and suggested the possibility that the DE screening method using FVA measurement combined with a symptom questionnaire may offer a new noninvasive screening tool to diagnose tear-film problems.[32,33]

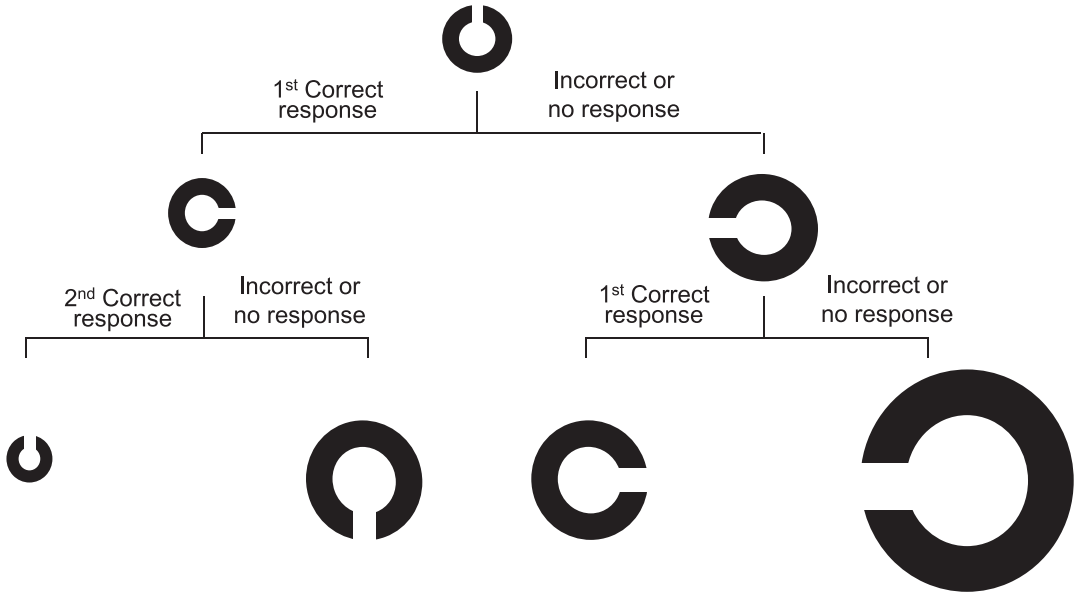

FIGURE 2. Optotype display of the FVA system. The optotype increases by one size automatically when the response is incorrect or when there is no response. On the other hand, the same-sized optotype is displayed at random again when the response is correct. The optotype decreases by one size when the next answer is correct.

By contrast, the McMonnies Dry Eye Questionnaire and Ocular Surface Disease Index are reliable and acceptable screening instruments that are used to subjectively discriminate patients with DE from non-DE subjects. These instruments are good predictors for discriminating aqueous-deficient DE from non-DE subjects. However, these are not as good at identifying marginal DE, categorized as short tear breakup time (BUT) DE.[34–36] What is meaningful in the screening tool using FVA system is that it would discriminate DE in VDT workers, who highly evolve to DE with tear instability.

EFFECTS OF OCULAR SURFACE ON FVA

Aqueous-Deficient DE

Evaluation of visual function in aqueous-deficient type of DE is possible by using the FVA measurement system. Several studies detected a reduction of FVA in aqueous-deficient type of DE,[28–30,37,38] and showed a positive correlation between FVA and optical quality.[38] One study also detected a significant reduction of VMR values in subjects with definite DE compared with control subjects with non-DE.[38] This reduction depends on the severity of ocular surface damage.

In line with these findings, Rolando et al.[39] and Huang et al.[40] demonstrated the visual impairment in DE with corneal epitheliopathy by measuring contrast sensitivity. Huang et al.,[40] Liu et al.,[41] and de Paiva et al.[42] assessed the optical quality, using the parameters of surface regularity index (SRI) and surface asymmetry index (SAI) of topography. They showed the high SRI and SAI values in the aqueous-deficient type of DE with punctate epithelial keratopathy and/or with ocular irritation.[40–42] Montés-Micó et al.[43] used a wavefront sensor and detected ocular higher-order aberration in DE as compared with non-DE. However, these measurement methods are used to evaluate visual function at a single point in time. As a sequential evaluation method of optical quality, Goto et al.[44] used the parameters of TMS-BUT (tear breakup time until a corneal refractive value change over 0.5 diopter by corneal topographs) and TMS-BUA (the ratio of breakup area to entire color-code area in 5 seconds). Kojima et al.[45] used the Tear

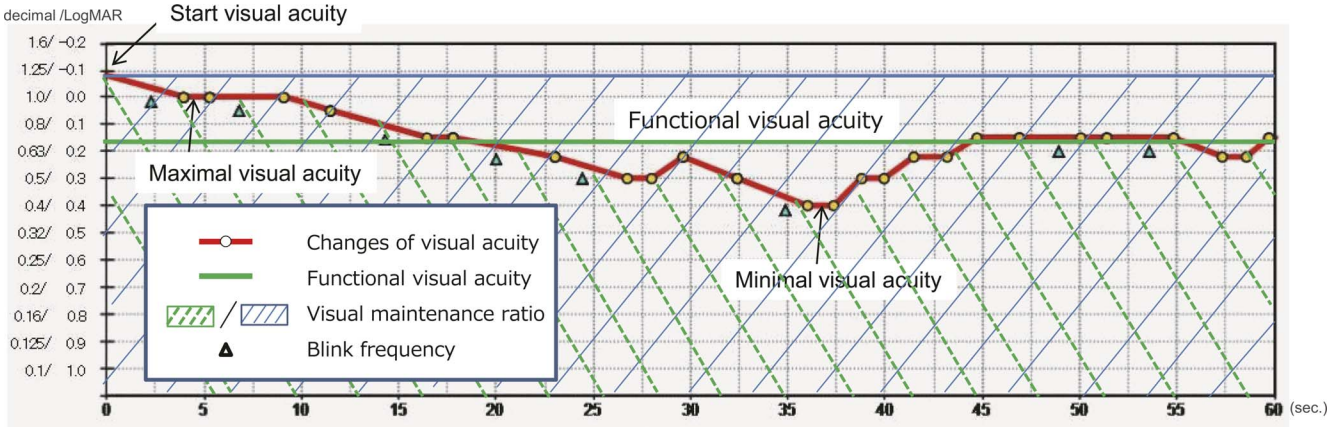

FIGURE 3. FVA measurements. Starting VA, FVA, VMR, maximal and minimal VAs, and blinks are recorded.

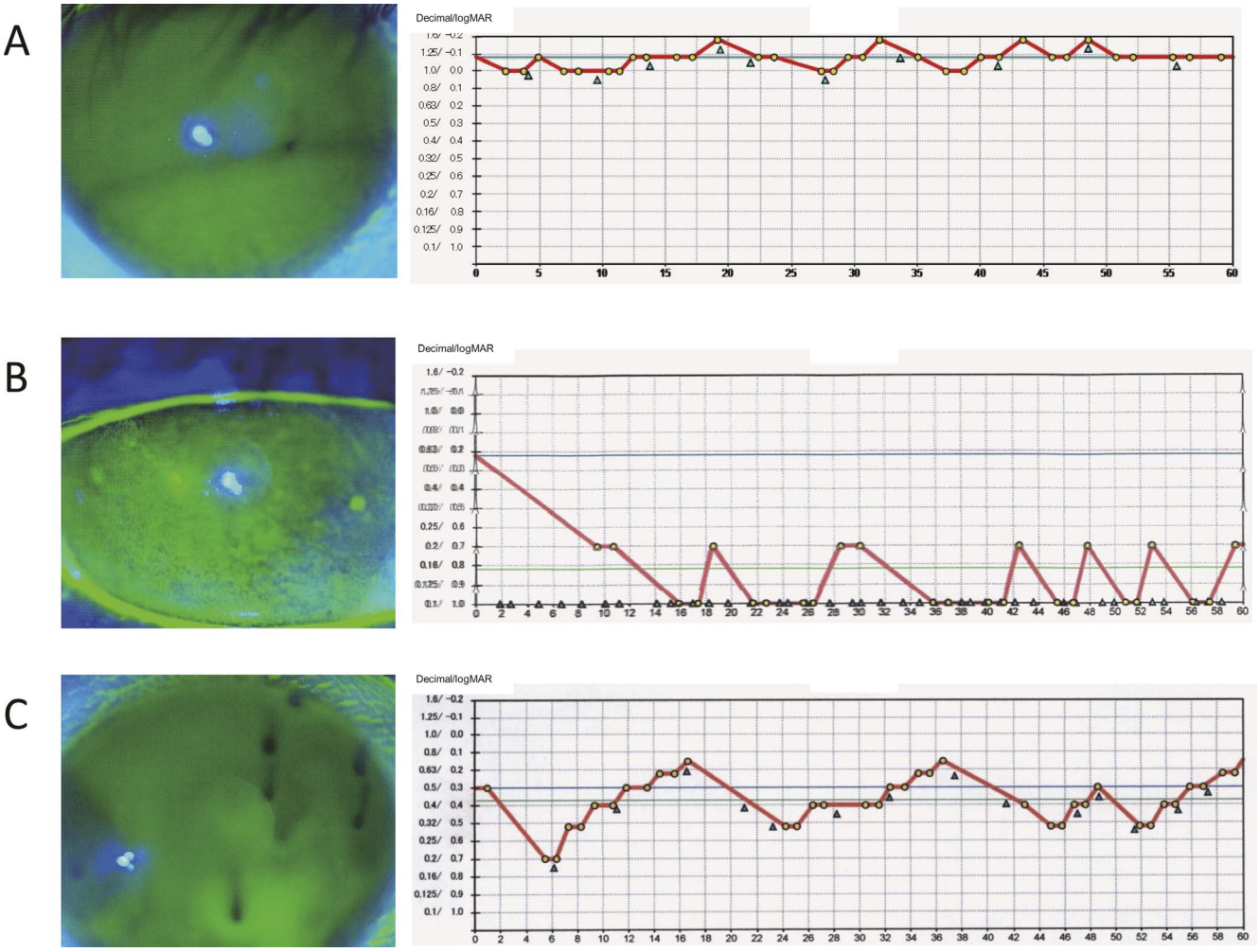

Figure 4. Ocular surface findings and sequential changes in visual acuities. (**A**) A healthy subject (a 38-year-old woman): tear film is stable and VAs over 60 seconds remain acceptable without fluctuation. (**B**) An aqueous-deficient DE (a 59-year-old woman): ocular surface is irregular and starting VA drops sharply in the first few seconds of the test and VA does not recover to the baseline VA level, remaining low even with blinking. (**C**) A short BUT DE (a 40-year-old woman): dry spots of tear film are observed and VA fluctuates over time, but returns to the baseline level after the reduction of VA.

Stability Analysis System, which can take 10 consecutive corneal topograms at 1 per second for 10 seconds. Koh et al.[46] used the sequential measurement of ocular higher-order aberrations. The latter two studies showed reduction of optical quality immediately after eye opening and without fluctuation in DE with epithelial damage at the corneal center.[45,46,47]

Figures 4A and 4B show the ocular surface findings and the typical pattern of FVA in non-DE and aqueous-deficient type of DE. VAs over 60 seconds remain acceptable without fluctuation in non-DE. By contrast, in aqueous-deficient DE, starting VA drops sharply in the first few seconds of the test and VA does not recover to the baseline VA level, remaining low. The irregular corneal surface causes a sharp decline in VA from the baseline VA due to epithelial damage. Decreased secretion of tears no longer loads to recover to the baseline VA even with blinking. This FVA pattern seems to be compatible with the results on the sequent optical quality that Kojima et al.[45] and Koh et al.[46] reported.

Short Tear BUT DE

Short tear BUT DE is characterized by decreased tear stability, minimal epithelial damage, and DE symptoms. Short tear BUT DE tends to be recognized as evaporative DE or be associated with meibomian gland dysfunction in the United States and in Europe; however, there is an increasing tendency to understand it as an isolated type in Japan, emphasizing the importance of tear stability. Unstable tear film also affects visual function. FVA measurement can detect impaired visual function in short tear BUT DE (Fig. 4C).[48,49]

The typical FVA pattern shows that VA fluctuates in the sequential changes of VA over time but returns to the baseline VA after the reduction of VA (Fig. 4C). This is possibly because VA is temporarily impaired due to the corruption of tear stability and regularity with eye opening, but complete blinking works on restoring VA to baseline VA levels due to the smoothing of ocular surface with tears. Koh et al.[50] demonstrated that higher-order aberrations show an increasing trend in short tear BUT DE, which may be compatible with the FVA pattern. These findings demonstrate that decreased tear stability alone has an impact on visual function.

FVA measurement system is also useful to determine the efficacy of treatments for DE.[51–54] We have previously shown the improvement on visual function after the use of diquafosol tetrasodium ophthalmic solution in short BUT DE by using the FVA system.[51] Similarly, Kobashi et al.[55] evaluated the effects of

diquafosol tetrasodium ophthalmic solution on the optical quality in short BUT DE, measuring the objective scattering index at 0.5-second intervals over 10 seconds without blinking with the double-pass instrument (OQAS II; Visiometrics, Cerdanyola del Vallès, Spain). They showed that intraocular scattering deteriorates with time in patients with short BUT DE and that diquafosol tetrasodium ophthalmic solution improves both BUT and intraocular scattering, demonstrating an improvement of optical quality. We also reported on the visual function of patients subjected to lacrimal punctal plug treatments.[53,54] Although tear function is improved after insertion of plugs into both upper and lower puncta regardless of with or without epiphora, FVA is improved only in the eyes without epiphora, leading to patient satisfaction with the treatment.[53] By contrast, the conventional VA testing does not detect visual changes in the eyes either with or without epiphora after the punctal plug treatments, thus not predicting the symptomatic satisfaction. This demonstrates that the FVA system is useful in assessing and quantifying vision-related symptomatology. Furthermore, another study showed that plug insertion into the upper punctum was significantly effective in the improvement of visual function, despite no effect on plug insertion to the lower punctum, whereas either upper or lower insertion was equally effective to improve the ocular surface condition.[54]

Stevens–Johnson Syndrome

One study has demonstrated the efficacy of FVA measurement for the assessment of visual function in mild or moderate cases of Stevens-Johnson syndrome.[30] FVA, but not conventional VA, was correlated with abnormal ocular surface findings and vision-related quality of life in mild and moderate cases of Stevens-Johnson syndrome, suggesting that FVA measurement can accurately detect the minutest visual deterioration related to ocular surface condition and vision-related quality of life.

Ophthalmic Solution to Non-DE

FVA measurement can also detect minimal changes of visual function after the administration of ophthalmic solution or ointment, even in non-DE. Ishioka et al.[19] reported FVA could detect the transient, short-term blurring of vision caused by viscous eye drops. Hiraoka et al.[56] reported the transient visual deterioration after the instillation of eye ointment. Interestingly, the correlation between the changes of VMR and the changes of optical quality in second-order aberrations was shown, demonstrating that FVA is a vision measurement reflecting the optical quality.

Future Directions

Subsequent studies showed that the FVA measurement is also applicable for the analysis of visual function accompanying refractive surgery,[20,56–58] contact lens wearing,[59,60] cataract and cataract-related disease,[61,62] retinal disease,[63,64] glaucoma,[65] amblyopia,[66] presbyopia,[67] and vehicle driving.[68,69] FVA reflects not only visual function related to tear dynamics, but also visual function related to quick recognition of the target, according to the measurement condition requiring a judgment time within the limited set time. The characteristics may enable a global visual function evaluation.

Cataract and Cataract-Related Disease

Yamaguchi et al.[61] reported improved FVA in cataract surgery patients with good preoperative VA, and recommended FVA for the evaluation of timing of surgery, visual quality, and changes in kinetic vision after phacoemulsification surgery.

Wakamatsu et al.[62] reported the improvement of visual performance after neodymium YAG (Nd:YAG) laser capsulotomy by using functional VA and the 10% low-contrast VA testing in patients after cataract, although corrected distance VA could not detect the changes before and after Nd:YAG laser capsulotomy. They also showed a correlation between optical quality and functional VAs or 10% low-contrast VAs.

Retina

Nishi et al.[63] evaluated visual function associated with early epiretinal membrane-induced changes. Of the patients with epiretinal membrane, the visual function of the affected and unaffected fellow eyes, which were both better than 1.0 as measured by a standard VA test, was evaluated by conventional VA, FVA, and contrast visual measurements. They showed that FVA and contrast VA reflected early changes in central visual function caused by epiretinal membrane, which were not detected by conventional VA.

Similarly, Tomita et al.[64] reported the utility of FVA in the assessment of subtle changes in central VA that reflect pathological findings associated with AMD.

Glaucoma

FVA measurement may be useful to diagnose early-stage glaucoma. The comparative study between patients with primary open-angle glaucoma (POAG) and healthy subjects showed that FVA and VMR were significantly worse in the POAG group, and that both FVA and VMR were correlated with abnormal macular ganglion cell complex thickness in the area of the papillomacular bundle,[65] demonstrating that FVA measurement may be a new diagnostic power for early glaucoma.

New Approach for the Assessment of Drivers' Visual Function

Based on the concept of FVA as the dynamic vision, the approach to assess drivers' visual performance has been attempted. Correlation was shown between FVA and subjective driving vision at night, which is decreased in aged drivers,[68] and correlated with useful field of view in elderly individuals.[69]

Conclusions

The FVA measurement system has been developed to assess visual function in DE. It is useful to detect minimal visual deterioration, which cannot be detected by conventional VA testing. It is also useful to determine the therapeutic effects of DE treatments. However, its use is expanding. It may be applicable to assess visual function not only in ocular surface diseases, but also diseases of the posterior segment of the eye or status affecting visual quality. This FVA measurement system is simple, noninvasive, and sensitive. Even though this method is available only in Japan, we expect it to be used worldwide.

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the patent right for the method and apparatus for the measurement of FVA (US Patent 7470026).

Disclosure: **M. Kaido**, P

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