Comparison of PD measuring devices

Part 1

Dr Wolfgang Wesemann investigates the accuracy of measurement and usage characteristics of four video centration devices and four pupillometers in a comparative study

Eye care practitioners' main activities include eye refraction and subsequent selection, mounting and dispensing of spectacles. For a pair of spectacles, the lens power and centration need to be correct. Centration errors may cause asthenopic problems, degrade the quality of stereoscopic vision and reduce the usable zones of progressive addition lenses.

Due to the increasing success of so-called 'personalised progressive addition lenses', accurate lens centration continues to gain in importance. Pupillary distance measurement alone is no longer sufficient. Additional fitting parameters such as back vertex distance, frame wrap angle and pantoscopic angle, need to be determined and specified for the lens order. Without precise knowledge of these parameters, it is not possible to compute personalised progressive lenses.

In a paper published in 1997, Wesemann *et al* presented information on the accuracy of measurement obtainable with a PD-ruler, pupillometer and the only video centration device which was commercially available at that time. Recently, however, several other companies have introduced video-based centration systems capable of measuring pupillary distance and all other relevant centration parameters.

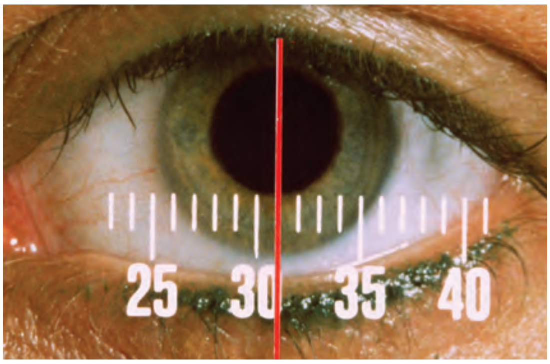
How user-friendly and how accurate are these new devices? This article study tries to answer these questions.

Devices

Four video centration systems were tested in this study:

- Essilor: 'Visioffice'
- Rodenstock: 'ImpressionIST'
- Ollendorf: 'Visureal'
- Zeiss: 'Remote Vision Terminal (RVT)'.

These four instruments provide a representative sample of all devices currently available on the market. It is important to note, however, that several other video centration devices are technically less advanced, as they are pure PD measurement devices and incapable of measuring additional centration parameters.



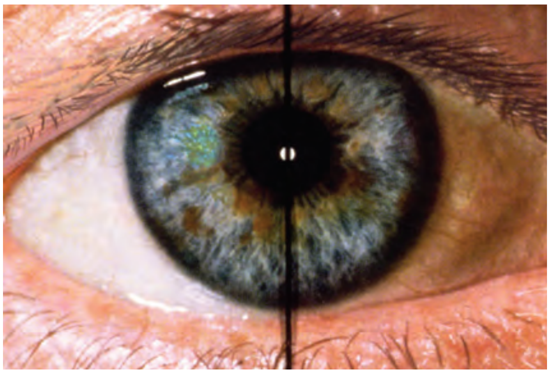


Figure 1 Centration according to the pupil centre (left) and corneal reflex method (right)

The video centration devices were compared to four state-of-the-art digital pupillometers that were purchased for the study.

- BON: PD-2
- Essilor: Digital CRP
- Rodenstock: Pm-100
- Topcon: PD-5.

All manufacturers were aware that their devices would be used within a comparative study.

Differences in measurement philosophies

Use of one or two cameras

The first technically 'mature' video centration system, ie Video Infral from Zeiss, used sophisticated technology including two cameras. One camera directly 'looked' at the subject's face, whereas the other simultaneously captured a side-on image using a mirror. Today, this 'two camera principle' including subsequent 3D analysis is only used by Rodenstock's ImpressionIST. All the other video centration systems use only one camera and capture two images one after the other.

Horizontal centration based on pupil centre or corneal reflex

There is no consensus among manufacturers on the best measurement technique. Some manufacturers demand that the device's hairline must coincide with the 'corneal reflex', whereas others require the hairline to be aligned with the pupil centre.

This causes an undesired problem, since the PD measured according to the corneal reflex method is on average 0.5mm smaller than the PD value measured according to the pupil centre method (Wesemann *et al*, 1997). With most people the corneal reflex is slightly shifted towards the nasal side relative to the pupil centre. The shift of the pupillary reflex relative to the pupil centre, however, is not a 'constant', but shows interpersonal variances. Today, it is still under discussion which centration method works better. If one looks at the image formation inside the human eye on a purely geometric-optical basis, the pupil centre method seems more appropriate. It must be noted, however, that the position of the pupil centre is not constant. This was investigated by Yang *et al* (2002). They found that the pupil centre normally undergoes temporal shifts, as the pupil diameter increases. This is due to the fact that the eye's iris opens asymmetrically. In most patients, spatial shift of pupil centre was smaller than 0.3mm per eye. One patient showed a 0.6mm shift per eye. In other studies dealing with the same topic, even greater shifts were observed.

The corneal reflex is independent of the pupil size and is always located at the same position. This is an advantage. Another advantage lies in its easier localisability. In most cases, Essilor's video centration system managed to localise the exact position of the corneal reflex in a fully automated manner.

If certain effects such as the Stiles Crawford effect of the first kind, are taken into account, the corneal reflex method may be underpinned by arguments from sensory-physiological findings. The issue of finding the ideal pupillary PD measurement method was addressed in a theoretical analysis published by Wesemann in 1996.

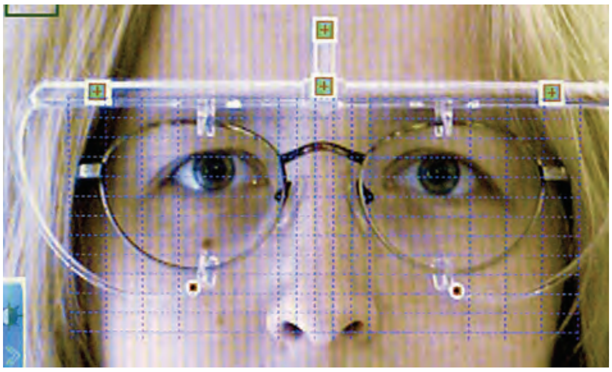


Figure 2 Screenshot of Essilor's Visioffice during measurement. The figure depicts the automatically detected red crosses on the green squares of the clip

Figure 3 Screenshot of Rodenstock's ImpressionIST during positioning of the patient. The figure shows the patient's face captured from the front as well as from below and the side

Vertical centration based on pupil centre or lower pupil margin

Different measurement philosophies also exist in vertical centration. On three devices (Visioffice, ImpressionIST and RVT), the fitting point height is calculated according to the so-called 'zero gaze direction' in distance vision. These three manufacturers assume that the fitting cross of the spectacle lens has to be centred exactly in front of the pupil centre when the wearer looks straight ahead with horizontal fixation lines.

Ollendorf's Visureal provides a somewhat smaller fitting point height in the preset mode. According to the manufacturer's specification, the calculated fitting point height corresponds to a downward gaze angle of exactly 2.25°. It is computed from the measured fitting point height by taking the vertex distance into account. This value corresponds to a 'centration relative to the lower pupil margin'. Another vertical centration method based on the 'principal gaze direction in distance vision' is also used by opticians. It corresponds to a significantly stronger downward head movement and gaze direction. Assuming that the patient's eyes are at 1.76m above floor level with the patient looking at the floor at a distance of 10m, a 10° downward head movement and gaze is required. The difference between both methods is approximately 1.1mm on average.

Practical use

Essilor Visioffice

Essilor's video centration system is very easy to use. Two video recordings are made with the patient looking straight ahead and with the head rotated 20° to the right. Analysing the video image is mere child's play. The computer automatically detects the patient's corneal reflexes as well as the green markers (squares) on the clip and the frame's horizontal line. The automatic detection of clip markers and corneal reflexes is done under real-time conditions in a highly reliable manner. In very rare instances, the markers detecting the patient's corneal reflex had to be readjusted manually. The examiner's task mainly consisted of explaining the measuring principle to the subject and aligning the rectangular measuring lines with the frame rims.

Although quite unusual, the patient is asked to actively cooperate during measurement. When looking straight ahead as well as in the lateral head position direction, the patient needs to move his head slowly from left to right and right to left. During the movement, they must constantly look in the mirror at the reflection of their nose. This task has to be carefully explained before starting the measurement. Without providing detailed instructions, the measurement process will not work properly. Our subjects, however, quickly understood what was expected.

Rodenstock ImpressionIST

The ImpressionIST is the only video centration system that captures two images with two cameras simultaneously. One camera looks at the face from the front and the other from below and the side. This is an advantage, as the patient needs to be properly positioned only once.

In order to position the subject properly, Rodenstock provides a carpet into which a line is woven that specifies the proper position of the subject's feet. Positioning the patient is relatively easy. The camera, however, does not have an autofocus system, but is set to a fixed distance.

The camera's 'direction of gaze' is also pre-adjusted. Therefore, the position of patients with large and small size shoes needed to be readjusted, to get a sharp picture of the patient's eyes on the monitor. Two light bars illuminating the patient produce very bright light and stay continuously lit. In some cases, these lights were perceived as dazzling. In the most recent version of the ImpressionIST, however, this problem has been solved thanks to the use of flash lighting.

Analysing the image via a touch-sensitive monitor is somewhat arduous. First, the corresponding part of the picture is magnified on screen. Then, the centration circle and each measuring line need to be adjusted in all directions on a step-by-step basis using a special adjustment pin. Therefore, Rodenstock's ImpressionIST required more time than the other centration systems.

Ollendorf Visureal

Ollendorf's Visureal offers the best image quality of all tested systems. Even fine details of the subject's eyes and spectacle frame are sharply rendered. Especially worth mentioning is the fact that this is achieved without using additional lighting. What is more, the patient is not bothered by continuous bright light or flash light.

Before starting the measuring process, a clip must be placed onto the spectacle frame. The clip design is very delicate compared to the clips used by Zeiss and Essilor. It is attached to the upper rim of the frame by means of two hooks and rests on the lower rim thanks to two perpendicular struts. This construction significantly reduces the clip's weight; however the advantage of such 'light-weight construction' is achieved at the expense of missing clamp holders. As a consequence, the clip dropped down several times during our measurements and had to be repositioned.

Taking side-on pictures with Ollendorf's Visureal is simplified with a remote-controlled motor providing a lateral adjustment for the camera. This is of high practical use where the patient is not exactly standing in a central position. Deviations can be easily compensated for by rotating the camera accordingly.

When taking side-on images, head position is somewhat critical. The clip should not be visible on the camera picture, ie neither obliquely from the front side nor obliquely from the rear ▶

side. In some cases, it was necessary to fine-tune the patient's position until the proper turn was achieved.

In addition, the version under test posed some 'challenges' in determining the frame wrap angle. To measure the wrap angle, a small additional clip had to be mounted onto the centration clip. In some cases, the additional clip underwent an unintended rotation. As a result, negative frame wrap angles were displayed. In these cases, the whole measurement had to be repeated. The manufacturer has presented an improved version of the measuring clip that hopefully solves the problem.

Zeiss Remote Vision Terminal

The Remote Vision Terminal from Zeiss is very easy to use. After the instument's height has been properly set, the patient looks at a flickering red fixation light (a laser speckle pattern) that does not stimulate accommodation according to the manufacturer. The patient stands at a short distance (70-150cm) away from the device. Within this range, distance can be selected as needed. The camera automatically focuses on their face.

At the start of our measurements, we often had problems with focusing. Contrast-rich objects located at a distance of 4.5m behind the patient irritated the autofocus system. We solved the problem by installing a separating wall (made of single-colour cardboard material) behind the patient. This restored the autofocus system's proper functioning.

Taking 90° side-on images was found to be more difficult with RVT than with Ollendorf's Visureal, because the patient is required to position himself at a specified place. The device requires that the patient's eye, the frame and the measurement clip are visible within a small, restricted area on the monitor. minor changes in the patient's posture (forward or backward movements) resulted in the patient's eye or the measuring clip being outside of the required area on the screen. Then, the patient had to be adjusted a second time and another picture had to be taken.

Data analysis is facilitated by the fact that the computer automatically tries to detect the patient's pupils and then aligns the fitting crosses with the pupil centre. For blue-eyed patients, automatic pupil detection works fairly well. Problems arise, however, with dark-eyed subjects. In two cases, the computer inadvertently placed the fitting crosses onto the rivet of a frame, producing a particularly strong light reflection. In some cases, automatic pre-centration was not possible.

Digital pupillometers

All digital pupillometers are manufactured outside of Europe. The PD-2 distributed by BON originates from Argentina-based 3B Optical Instruments Corporation, Essilor's Digital CRP is made in China. The two remaining devices (PM-100 from Rodenstock and PD-5 from Topcon) originate from Towa, a Japanese company. The two last-mentioned devices are of seemingly identical construction. Differences in design relate to the products' 'outer' aspects only. Interestingly, the sales price of the two pupillometers is very different.

Handling of all devices was found to be very simple. All are equipped with a 'paddle', allowing one eye to be occluded when needed. Reading of right/left PD values is done from a digital scale graduated in 0.5mm increments.

The price of video centration systems and pupillometers differs considerably. Video centration systems cost more than €5,000. In contrast, conventional pupillometers are priced below €500.

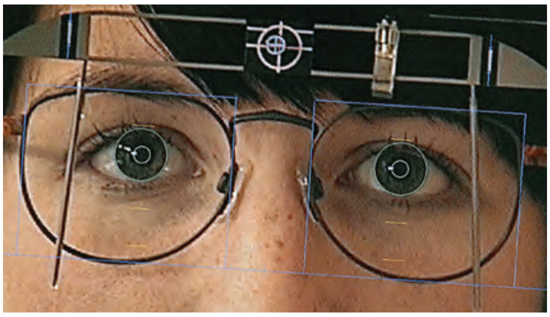


Figure 4 Screenshot of Ollendorf's Visureal during analysis **The figure depicts the clip fitted onto the frame. It also illustrates the adjusting markers for the patient's pupils and boxing system**

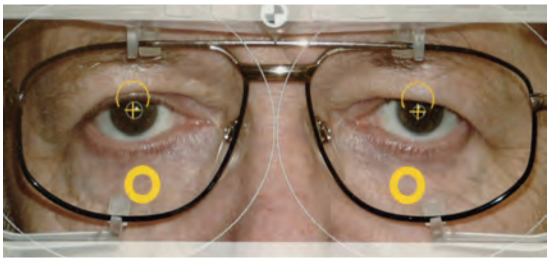


Figure 5 Screenshot taken from the RV Terminal (Zeiss RVT) during analysis

Additional functionalities of video-based centration systems

All four video centration systems offer further options, such as comprehensive eyewear consultation using frame/lens consultation modules. Practitioners can demonstrate the benefits inherent in various lenses. Video clips highlighting the respective product benefits can be presented to patients. Also, websites dedicated to ophthalmic and optometric contents may be accessed. However, these features have not been compared.

Handling problems

In most cases, measuring was easy, except in relation to a few things.

Problems associated with 90° side-on images

Two digital images are taken with the Visureal and RVT system, ie a front view and a picture with the patient's face turned through 90°. For both devices, it was found that (in the absence of further

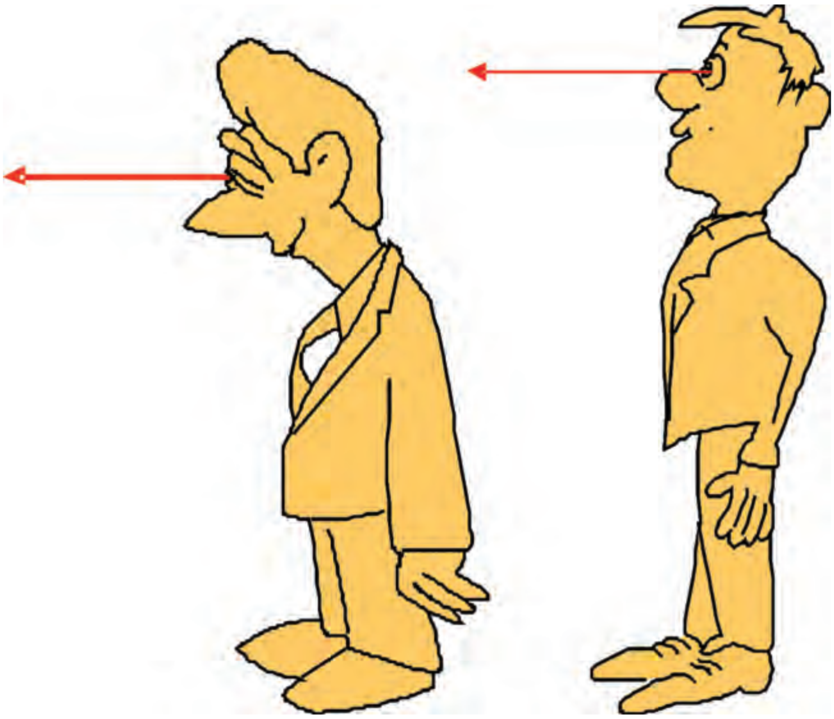


Figure 6 'Military' and 'slouching' posture (from: Essilor)

explanation) the subjects did not know in which direction to look and how to position their head. As the manufacturers did not provide a fixation target when capturing side-on pictures, our subjects were looking in completely different directions. Consequently, unreliable values for the pantoscopic angle and the fitting height were found during our first trial measurements. To remedy this problem, an additional eye chart was installed in the zero gaze direction of the subject (rotated 90°) and they were told which letter on the eye chart to look at. In this regard, manufacturers should provide better support to the practitioner.

Problems associated with 'natural head and body posture'

During measurement, patients should adopt a 'natural head and body posture'. Here, we have to cope with a major and complex problem. Often, in a real-life situation at the practice, the patient is not relaxed at all and unable to maintain their natural (habitual) posture.

Very often, they do not know what their 'normal' head posture actually is, nor do they know how to position themselves in front of the device. Some patients, for example, show the following two posture profiles (Figure 6):

a) M*ilitary posture*
The person is standing tall and upright in front of the video centration system with their arms hanging straight down to the trouser seams and with their head slightly tipped backwards. For this type of person, the measured fitting height will be too low, because the head is tilted back.

b) *Relaxed/slouching posture*
The person is standing in front of the video centration device with their stomach pushed forward, their head slightly tilted downward, and their hands pushed into the trouser pockets. For this type of person, the measured fitting point height will be too high, as the person is gazing slightly upward when looking at the centration system's fixation target.

We believe that the problem of 'natural head and body posture' cannot really be solved. The examiner should at least make sure that...

a) the person's arms dangle relaxed down both sides of his body

b) the person does not stand tall and erect like a soldier

In case of doubt, the patient should begin the measurement by walking around the room to become more relaxed.

Problems associated with special eyewear designs

Clear transparent eyewear

Big problems occurred with transparent spectacle frames, because the operator had difficulties in detecting the rim of the transparent frame. This led to errors in adjusting the centration lines.

Round/sharp-angled frame styles

Round or sharp-angled frame shapes led to problems on those video centration systems where a clip has to be placed onto the frame (Visioffice, Visureal and RVT). On frames with round-shaped upper rims, the clip suddenly slipped off, requiring the examiner to restart the measurement process. In so me cases, frames with laterally slanted upper rims were equally problematic. On so me frames with double bridges, the clip could not be attached according to the manufacturer's instructions, as the retaining clamps were located at the border of the double bridge and therefore lacked stability.

Nylor rimless designs with demo lenses

On Nylor frames with demo lenses, the subject's pupil centres were difficult to ▶

detect due to the bothering reflections produced by the uncoated dummy lenses. This problem was not investigated further as all measurements reported here were taken with frames that were not fitted with dummy lenses.

Ti me required for one measurement

The time required for the entire measurement process, from introductory explanations to the final print-out of the results, was measured with a random sample of subjects.

In unproblematic cases, the mean measuring time was approximately 2 min 40 sec, with Essilor's Visioffice, Ollendorf's Visureal and Zeiss RVT. When problems occurred, eg when a side-on picture had to be taken a second time, measuring time increased to some 3 minutes and 20 seconds on average. These values include the time needed for keyboard data entry as well as for adjusting the centration lines via mouse drag. The use of a touch screen normally requires much more time.

The shortest measuring and interpretation times were found with Essilor's Visioffice, as in most cases it automatically detected the clip markers and corneal reflexes. This device, however, required a little bit more time for introductory explanations. So, all in all, the three devices did not show substantial differences in measuring time.

With Rodenstock's ImpressionIST, a problem-free measurement took about 4 minutes and 20 seconds. This increase in measuring time was mainly due to the much more labour intensive method of adjusting both the pupil centres and the centration lines on the tactile touch screen. All centration lines need to be adjusted in an arduous step-by-step process by 'tapping' the screen with a touch pen. So, measuring time with Rodenstock's ImpressionIST is about 1 and a half minutes longer than with the three other centration devices. This is annoying when the practitioner wishes to perform numerous PD measurements in succession as we did. In most cases, however, the question of whether the whole PD measurement process (including analysis) takes 2:30 or 4:00 minutes seems to be of minor importance for the usual business in practice.

Assessment of handling aspects

Assessing the practical use of the four devices is not an easy task, since all video centration devices have left a positive impression. Table 1 provides an evaluation for eight key features. When comparing the total number of positive points, all perform almost equally well.

TABLE 1

Evaluation criteria	Essilor Visioffice	Ollendorf Visureal	Rodenstock Impressionist	Zeiss RVT
1 Adjusting the required distance is easy. The eyes are focused automatically	+	+	o	+
2 Computer assists in aligning the hairline with the corneal reflex or pupil centre	++	+	+	+
3 Image taken by the camera shows superior quality	+	++	+	+
4 Measuring time is short	++	+	o	+
5 The person quickly understands what to do	+	+	++	+
6 The eyes are not dazzled	+	++	+ (1)	+
7 Measuring clip is easy to mount and provides a secure fit	+	o	++ (2)	+
8 User instructions are informative, comprehensive and clearly arranged	+	+	+	o
Total number of good points	10	9	8	8

Short assessment of the practical use of four video centration systems (using the following evaluation scale: ++ = very good, + = good, 0 = satisfactory)
(1) remark concerning criteria # 6: Assessment of Rodenstock's ImpressionIST was based on the 2008 version equipped with light bands. In the new version, these light bands have been replaced with a flash lighting system.
(2) no measurement clip needed.

Summary of handling aspects

We did not encounter any real serious problems in operating the four video centration devices. Quite the contrary, working with them is a pleasure. All video centration devices gave a technically mature impression and strongly impressed the subjects.

It is very important that the manufacturer's staff (in charge of providing on-site training) is fully familiar with all practical (handling) tricks. Moreover, all potential users should be made aware of the utmost importance of properly adjusting the centration lines.

Many eye care practitioners are still unaware that less precise adjustments may lead to large measurement errors. In addition, written instructions for use should be provided to allow the user to reread all relevant information contained therein. Should potential users be unable to participate in the training, the practice manager should assign an employee to provide detailed explanations on the device's practical use. They should also verify, at a later time, the proper use of the device within a quality management policy. In this regard, several companies provide invaluable customer service helplines to answer all questions.

Several video centration systems can be operated either via mouse or via touch screen. Today, a touch screen looks stylish and seems to be more popular and more appealing, but in our opinion, the use of a keyboard and a mouse makes operation faster and more accurate.

All devices have their own little peculiarities you need to get accustomed to. On the RVT system, for instance, the need to confine the subject's eye and spectacle frame to a small window on-screen when taking side-on pictures was annoying at first. In the Visureal device, the typeface on the Laptop screen was very small. Older users found it difficult to read the text on the screen. With Rodenstock's ImpressionIST, the user gets nervous over the painstaking act of touch-screen 'tapping'. As to Essilor's Visioffice, the optician might be a little afraid of the customer who does not understand how to properly move their head. Fortunately this kind of situation did not arise during our study.

However all these small irritations, vanish as the operator becomes more accustomed to the use of the device. ●

● In the next issue, the author will take a closer look at the degree of accuracy provided by these centration devices.

● Full list of references with part 2.

● **Dr Wolfgang Wesemann** is based at the University of Cologne

● This paper has been supported by

Comparison of PD measuring devices

Part 2

In the first part of this review of PD measuring devices, **Dr Wolfgang Wesemann** described handling characteristics. Here he presents the results of comparative measurements

One thousand centration measurements were performed. The measurements were grouped into two different studies:

- **Repeatability study:** Nine subjects were measured five times with each of the eight centration devices under test. These repeatability measurements were not taken in immediate sequence. Only following a complete measuring cycle with all eight instruments was completed, another cycle was started. This required refastening the measuring clip to the spectacle frame as well as readjusting the subject's posture in front of the centration system. This procedure intended to simulate the real-life situation in an optical practice and shows how accurate each instrument can replicate the results on the same person.
- **Serial study:** Eighty subjects were measured only once with each of the eight centration devices. The eight measurements were taken consecutively within 45 minutes. Testing order of centration systems was varied on a random basis. All subjects received verbal instructions before measurements were taken. Detailed explanations of how the ideal head and body position should be were provided. During measurement, care was taken that the subject's posture was acceptable and the subject was properly looking at the fixation target. This procedure highlights the measurement accuracy of people not familiar with the devices

Subjects/examiners/data analysis

Most subjects were students and lecturers of the Cologne School of Optometry. Pupillary distances varied from 56 to 74mm. Mean value was 62.25mm. None of the subjects showed manifest squint. All spectacle frames had been carefully fitted. Two subjects were wearing large-sized eyewear, making it impossible to attach the Visureal measuring clip to the subject's frame. For two other subjects, data on the Zeiss RVT printout were missing for unknown reasons. These four subjects were excluded from final data analysis.

All measurements were taken by nine examiners. All examiners received an extensive training from the respective manufacturers. Additional written documentation was provided and additional questions regarding specific aspects of use or interpretation of measurement data were answered by experts from the different companies via a smoothly running hotline. Prior to all research measurements, numerous trial measurements were carried out that were not included in the final analysis.

'Gold standard'

When comparing results provided by the various measuring devices, the examiner always had to face a seemingly unsolvable problem. The 'true' value of the pupillary distance (PD) of a subject, for example, is not known and cannot be exactly determined from the results displayed by the various measuring devices. Of course, each manufacturer will argue that 'its' device delivers accurate results. However, if one of the tested devices is assigned a particularly high degree of accuracy, this would be unfair with regard to the other devices. So, this problem can only be solved by calculating the mean value of all eight results. This mean value represents the 'best possible compromise'. In the literature, it is often referred to as 'gold standard'.

Example: For subject number 53, measurements performed with the eight centration devices showed the following PD values: 61.7/62.4/62.6/62.0/61.5/61.0/62.2 and 60.5mm. The subject's 'true' PD is unknown. In this case, the mean value is 61.74mm. This mean PD value is regarded as close as possible to reality. The same averaging approach was used for all other parameters as well.

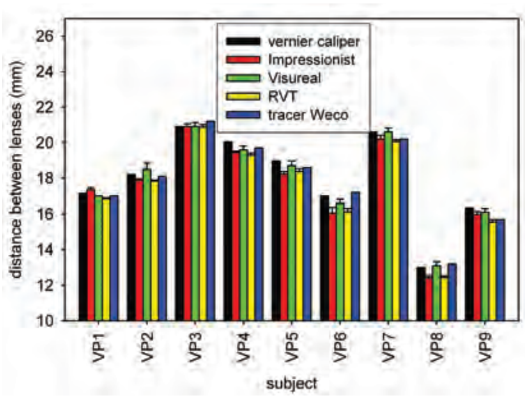


Figure 1 Comparison of bridge sizes (distance between lenses), measured using three video centration systems as well as two other methods (mean value and standard deviation determined from five measurements respectively)

Results of comparative measurements

Frame measurements

Frame parameters were measured using three video centration devices. Essilor's Visioffice was excluded from the analysis, because it only printed the minimum diameter of the uncut spectacle lens.

In addition, frame parameters were measured using:

- A vernier calliper and a modified thickness gauge (for measuring groove depth) and
- The tracer of a numerically controlled edger.

In the case of Rodenstock's ImpressionIST and the RVT from Zeiss, measuring lines have to be aligned with the boundary between frame rim and lens. Afterwards, the assumed groove depth is added by the system in order to obtain the actual lens size. To achieve this, the computer uses standard groove depths for metal and acetate frames.

In the case of Ollendorf's Visureal, the examiner had to align the measuring lines with the estimated position of the 'groove bottom'. The lens size determined in this way is already the final value.

Figure 1 shows the bridge sizes (distance between lenses) obtained in repeated measurements. All results displayed by the video centration devices are in good agreement with the values measured with the vernier caliper and the tracer. Differences were smaller than 0.5mm. Similar deviations have been found in the serial

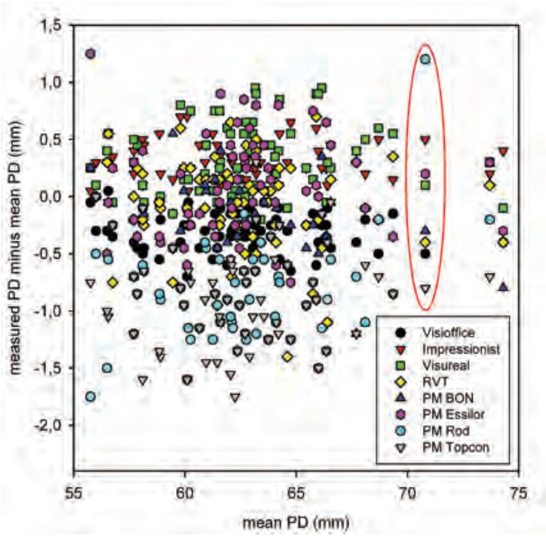


Figure 2 Bland-Altman diagram of PD measurement values for 76 subjects. The Y-axis shows the difference between the individual PD value (measured with each of the eight devices) and the average PD of the subject. The X-axis plots the mean PD value for each of the 76 subjects. The red ellipse highlights the eight differences computed for subject 'SK'

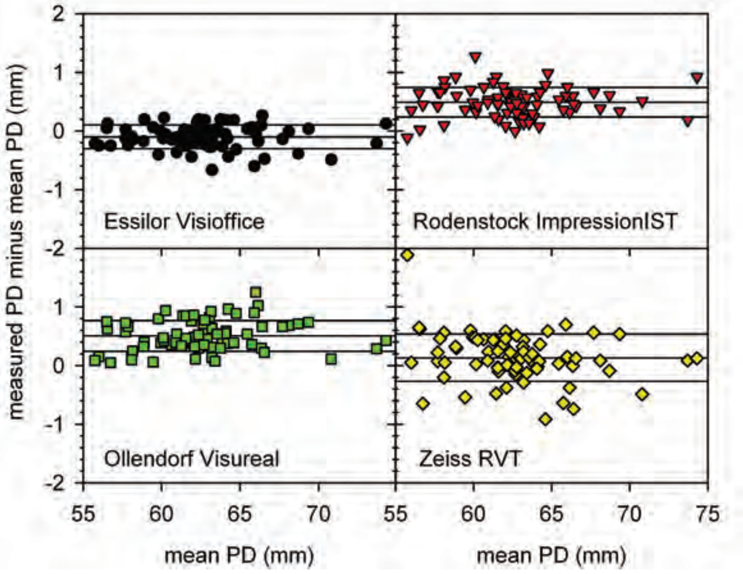


Figure3 Bland-Altman diagram of PD measurements displayed by four video centration devices for 76 subjects. The three lines in either diagram represent the mean value and standard deviation of all 76 measurement values

study. In conclusion, frame parameters such as bridge size, vertical boxed size and horizontal boxed size may be determined by video centration systems to a high degree of accuracy. The errors are partially due to differences between actual and assumed bevel depth.

Pupillary distance (PD)

When measuring PD values, we not only found system-specific measurement uncertainties, but also substantially systematic differences.

Figure 2 shows an analysis of the pupillary distance (PD) values measured with all eight centration devices. It is presented in the format of a Bland-Altman diagram.[1,2,3] The diagram plots the individual deviations from the gold standard against the mean PD value for each subject involved.

How to read the Bland-Altman diagram in Figure 2: First, for each of the 76 subjects involved in the serial study, the mean PD value was calculated across all eight devices, resulting in a mean PD of 70.8mm for subject 'SK'. Next the difference between the measured PD and the mean PD value was calculated for each centration device. Then, the eight differences were plotted above the x-axis at 70.8mm (highlighted by the red ellipse). For all other subjects, differences were calculated in the same way and plotted above the mean PD value of the respective subject.

If the y-value of a data point in Figure 2 is exactly zero, the respective device has displayed a PD value that is identical to the mean value across all devices. A positive difference shows that the device under test has displayed a larger PD value as compared to the gold standard, whereas a negative difference indicates a smaller PD.

At first glance, all PD data show a surprisingly large scatter. Differences larger than 1.5mm between the device with the highest PD value and the device with the smallest PD value are the rule rather than the exception. So, it is obviously an illusion to expect all PD measuring devices to provide identical results.

Scattering of measurement values/Uncertainties associated with PD measurements

The broad distribution of the data diminishes sharply when the results obtained by different devices are considered separately. Figure 3 shows individual Bland-Altman diagrams for all four video centration systems. The three lines represent the respective mean and standard deviation. The centre lines for Visioffice and Zeiss RVT hit the y-axis close to zero. In other words, these devices displayed on average almost exactly the value of the gold standard. The average PD measured by Rodenstock's ImpressionIST and Ollendorf's Visureal is approximately 0.5mm larger.

The standard deviation denotes how much the measured data scatter around the average. When data is normally distributed, 68 per cent of all data lies within an interval of +/- one standard deviation from the mean. The standard deviation, however, does not characterise systematic deviations from the 'gold standard'. It mainly specifies unavoidable measurement errors caused by the device or the examiner. In scientific studies, the so-called 95 per cent confidence interval is alternatively being used. This interval is twice as large as the standard deviation and comprises approximately 95 per cent of all measured values.

All standard deviations 'σ' of PD measurements found during our repeatability study and our serial study are shown in Table 1.

Essilor's Visioffice performed best during both the repeatability study ($\sigma = \pm 0.09$mm) and serial study ($\sigma = \pm 0.20$mm), delivering a particularly high repeatability.

Rodenstock's ImpressionIST and Ollendorf's Visureal also showed very good values ($\sigma = \pm 0.25$mm) during both studies. During the repeatability study, Zeiss' RVT achieved very good test scores ($\sigma = 0.13$mm), but showed significantly higher scattering during the serial study ($\sigma = \pm 0.40$mm).

The standard deviation of all pupillometers was similar for both the repeatability study and serial study, amounting to an average value of approximately $\sigma = \pm 0.35$mm.

All in all, standard deviation for pupillometers during the repeatability study was roughly twice as high as for video centration systems. Hence, video ▶

centration systems performed much better than pupillometers. During the serial study, however, the difference between video-based devices and pupillometers was not so high.

Systematic differences in PD

When considering the data points in Figure 2 in more detail, characteristic differences can be found. The green squares, for example, tend to be located in the upper part of Figure 2, whereas the grey triangles tend to be located in the lower part of the graph. The considerable systematic differences become evident when the mean deviation from the 'gold' standard is calculated. The result of this computation is shown in Figure 4.

The red symbols indicate systematic differences found during our repeatability study. The green symbols show systematic differences in our serial study on 76 subjects. Although measurements were performed on different subjects at different points in time, nearly identical results were obtained in the repeatability and the serial study for each device. This confirms that systematic differences really exist and that the nine examiners in charge of the study have taken reliable measurements.

Figure 4 shows that the results provided by Visioffice, RVT and BON centration devices deviate by less than 0.2mm from the mean across all devices. PD values measured with Rodenstock's and Ollendorf's centration devices were found to be larger by approximately 0.5mm than the 'gold' standard. Rodenstock's and Topcon's pupillometer provided PD values that were approximately 0.8mm smaller than the mean PD value.

The systematic differences of 1.3mm between the smallest and the largest PD are found even when utmost care is taken during the measurement. The differences are not caused by measurement uncertainties or setting errors made by the examiner, but are exclusively due to system-specific calibration differences and differing measuring principles.

Compensation of different measurement philosophies

The large differences between the various centration devices diminish somewhat when the difference between the 'corneal reflex method' and the 'pupil centre method' is taken into account. According to the study performed by Wesemann *et al* 1997 and the remarks provided in Part 1, we may expect that the mean PD based on the subject's pupil centre will be 0.5mm larger than the mean PD based on the corneal reflex. In order to compensate for this difference, a correction value of 0.5mm was added to the results of those devices working on the basis of the corneal reflex method. Then, the mean value was recalculated across all devices. The effect of this correction is shown in Figure 5.

When comparing the recalculated data points in Figure 5, it can be seen that Essilor's Visioffice, Rodenstock's ImpressionIST and Ollendorf's Visureal display almost identical PD values. The remaining differences are extremely small and amount to less than ±0.05mm. PD values measured using the RVT from Zeiss are approximately 0.35mm smaller as compared to Visioffice, ImpressionIST and Visureal.

Looking at Figures 4 and 5, it appears as though Rodenstock's and Topcon's pupillometers display values that are too small. In Figure 4, average PD values are 0.8mm smaller than the mean value, whereas in Figure 5, average PD values are still 0.5mm too small.

Pantoscopic angle

The pantoscopic angle is a parameter that is technically simple to measure. In the case of the Visureal device, for

TABLE 1
Standard deviation of PD measurements taken during repeatability and serial study

	Standard deviation of PD measurements	
Device	Repeatability study	Serial study
Visioffice	0.09mm	0.20mm
ImpressionIST	0.24mm	0.25mm
Visureal	0.24mm	0.26mm
RVT	0.13mm	0.40mm
BON pupillometer	0.47mm	0.30mm
Essilor pupillometer	0.29mm	0.35mm
ROD pupillometer	0.32mm	0.39mm
Topcon pupillometer	0.29mm	0.37mm

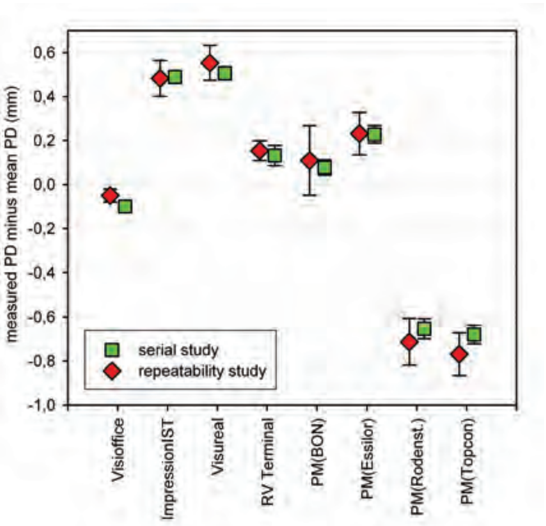


Figure 4 Systematic differences between PD measurement results for eight centration devices. Error bars show the standard error. The term 'standard error' denotes the standard deviation of the mean. The standard error is calculated by dividing the standard deviation by the square root of the number of measurements. It defines a confidence limit for the mean value. Since a large number of subjects (ie 76) took part in our serial study, the standard error is very small. In other words, the systematic difference between the eight centration devices was determined with a high degree of confidence

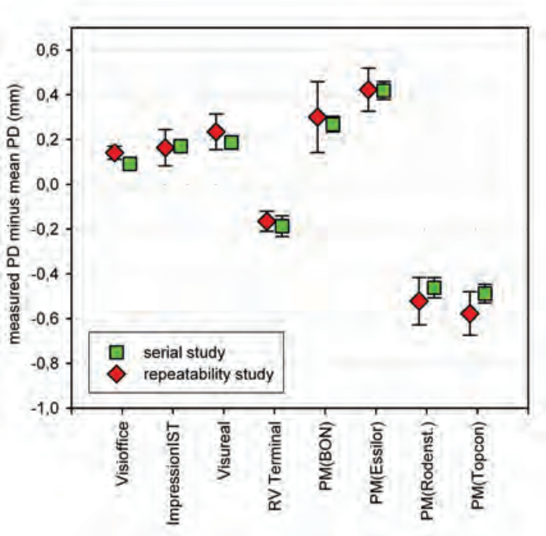


Figure 5 Systematic differences between PD of the instrument indicated and the average PD across all instruments after differences between corneal reflex method and pupil centre method have been compensated. Now, differences between Visioffice, ImpressionIST and Visureal are smaller than ± 0.05mm

example, pantoscopic angle as well as head rotation is calculated from the displacement of a small circular mark with respect to a larger circle (Figure 6). In a similar manner, Visioffice and RVT calculate the pantoscopic angle from the relative position of specific measuring references.

Human measurement errors which may occur due to an inaccurate adjustment of centration marks can be excluded, because the video centration systems are able to detect the relevant measuring marks automatically. Therefore, one could think the pantoscopic angle is a parameter, that can always be measured to a high degree of accuracy. However, this is not the case.

Figure 7 shows results obtained for the pantoscopic angle on nine subjects and five repeated measurements. Differences of up to 5° in successive measurements are the rule rather than the exception and occur on all four devices.

As it is technically simple to measure pantoscopic angle, different results are not due to measurement errors inherent in the devices under test. Instead, the different pantoscopic angle values must have existed at the time of measurement!

This is even more remarkable when considering the fact that the nine subjects involved in the repeatability study were experienced subjects and fully aware of the measurement goals. They all knew that they should try to assume the same head and body posture in the best possible way. The differences still found during the five successive measurements clearly show how difficult it is even for experienced subjects to maintain a 'natural head and body posture'.

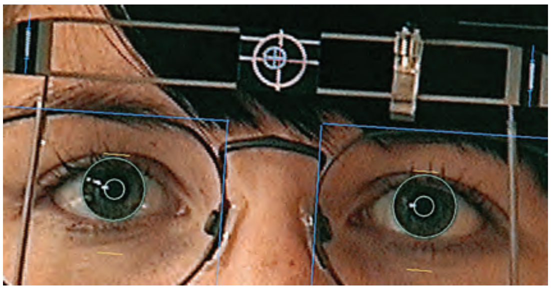


Figure 6 A small circular mark, mounted on the measurement clip above the nose will show a parallax displacement with respect to a larger circle when the plane of the frame is tilted. Both circular marks are automatically detected and analysed by the system

Given the uncertainties found during our repeatability study, it is not surprising that the results obtained in the serial study also show substantial differences. On all four devices, the standard deviation of pantoscopic angle measurements amounted to around ±1.9° for the repeatability study and to approximately ±2.1° for the serial study.

On average, Essilor's Visioffice and Ollendorf's Visureal provided pantoscopic angle values that were approximately 1° smaller than the group average, whereas the RVT from Zeiss provided a pantoscopic angle value that was 2° greater than the group average. These differences were small yet significant ($p<0.001$, Student-Newman-Keuls test).

Fitting point height

Fitting point height is the second most important measuring parameter. This particularly applies to progressive addition lenses (PALs). If PALs are fitted too high, the wearer will look through the progressive corridor during car driving, so that they see the road less clearly. If the lenses are fitted too low, a large downward gaze is required in order to see clearly for near distance tasks.

All video centration systems operate in the so-called 'primary position'. The subject's lines of sight are directed horizontally to the mirror image of their own face (= nose bridge in the case of Visioffice and ImpressionIST) or, alternatively, to a fixation target (laser speckle pattern in the RVT and red light in the Visureal). This viewing direction is also called 'zero gaze direction'. The video camera (not visible to the subject) is positioned at approximately the same level as the subject's eyes.

Figure 8 shows the fitting point heights determined for the right eye during the serial study. For the sake of clarity, mean fitting point height was calculated for each subject. Then, all subjects were sorted in ascending order of mean fitting point height. The reasons for this conversion have been explained under the heading 'Pantoscopic angle'.

When fitting point height for the left eye is considered as well, a total of 152 measurement values for each device can be used for statistical analysis. All four devices show only small systematic differences. On average, the systematic differences between fitting point heights was less than ± 0.5mm.

Standard deviation amounted to approximately ± 0.84mm. In other words, individual fitting point heights vary considerably, although great care was taken in properly fitting the spectacle frame and in instructing

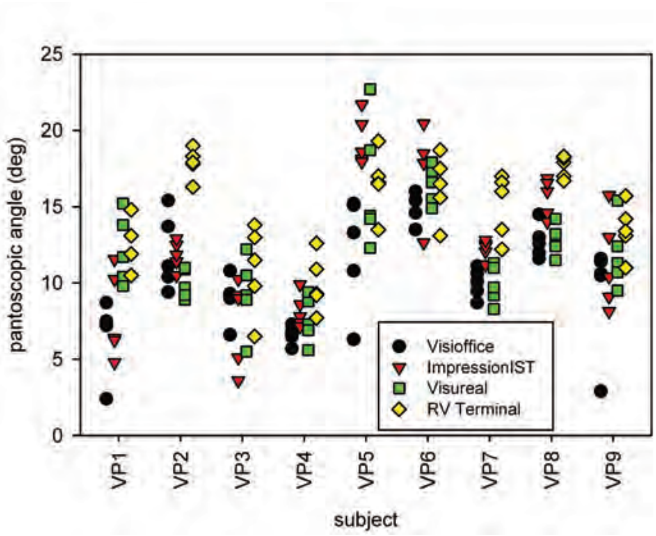


Figure 7 Pantoscopic angle measurements for nine subjects.measured five times with each device. The figure shows all individual results

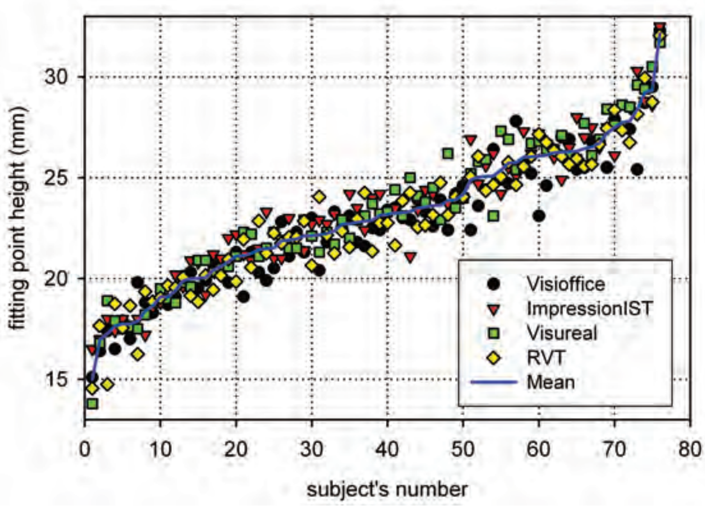


Figure 8 Fitting point height (right eye) for 76 subjects, sorted in ascending order

all subjects on proper head and body posture. This is not surprising with regard to the discussion under Pantoscopic angle. It seems that during repeated measurements most subjects were unable to assume the same head posture in front of the devices, even if detailed instructions were provided beforehand.

Back vertex distance

Figure 8 shows the results of vertex distance measurements obtained during the repeatability study. Subjects VP4 and VP8 provided very similar values with small standard deviation across all four devices. The data of subject VP7 scattered much more. On subject VP9 Essilor's Visioffice and Rodenstock's ImpressionIST displayed vertex distance values of 12mm and 7mm respectively with very high repeatability. The reason for the big difference is not clear.

Figure 9 shows the deviation of the measured vertex distances from the mean value of the serial study. Vertex distance measurements show only small systematic differences. On average, all four devices are close to the 'gold' standard.

The overall variation in vertex distance is shown in Table 2. The smallest variation was recorded in Rodenstock's ImpressionIST, followed by Essilor's Visioffice and Ollendorf's Visureal. Overall, variations show similar levels for all four devices. On average, a standard deviation of ±0.77mm (repeatability study) and ±1.28mm (serial study) was found.

TABLE 2

Uncertainty of vertex distance. The table shows the standard deviation for repeated measurements (repeatability study) as well as the standard deviation of the difference from the gold standard (serial study)

	Mean standard deviation of vertex distance measurements	
Device	repeatability study	serial study
Visioffice	± 0.80 mm	± 1.16 mm
ImpressionIST	± 0.68 mm	± 1.10 mm
Visureal	± 0.87 mm	± 1.36 mm
RVT	± 0.75 mm	± 1.26 mm

Frame wrap angle

Frame wrap angles were measured with all four video-based centration systems as well as with a simple mechanical measuring tool (Figure 11). The manual measurements with the tool were performed by two opticians and are labelled 'Rod meas tool 1 and 2' in the legend of Figure 12.

The histogram in Figure 12 shows similar frame wrap angles for all four devices. Values found with the manual measuring tool were either identical or tended to be slightly larger (for subject VP2, VP6 and VP7).

Mean standard deviation across all nine subjects was ± 0.81° for Essilor's Visioffice (serial study), ± 0.67° for Rodenstock's ImpressionIST, ± 1.83° for Ollendorf's Visureal and ±0.55° for RVT from Zeiss, providing altogether satisfactory levels of accuracy. The relatively high levels of uncertainty found in Ollendorf's Visureal might be due to the fact that the fit of the wrap angle clip was too loose. Ollendorf recently presented a new clip allowing for more precise wrap angle measurements. However, there wasn't enough time left to test the new clip under the present study.

Standard deviation was smaller for the mechanical measuring tool, amounting to ±0.35° for optician number 1 and ±0.32° for optician number 2. Hence, accurate measurement results can also be achieved by using a low-price measuring tool.

Summary and discussion

Pupil centre – corneal reflex

It is annoying that manufacturers propose two competing measurement philosophies. Five companies recommend that pupil centration should be done relative to the 'corneal reflex', whereas three other companies advocate the use of the 'pupil centre' method. Obviously, this causes a partial loss of accuracy. With some slight exaggeration, the manufacturers' specifications can be compared with two carpenters whose tasks consist of measuring the size of a rectangular table. One carpenter has to measure the length of the table, whereas the other measures its width. It is clear that the two methods will deliver different results. Unfortunately, manufacturers have not yet agreed upon a standardised procedure, nor are they expected to do so in the foreseeable future. On the contrary, a third new measuring philosophy, ie 'PD measurement based on the eyes' centre of rotation' was presented recently.

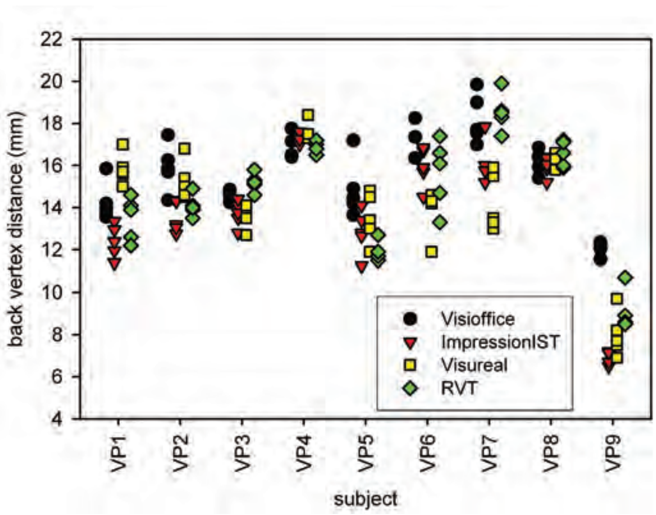


Figure 8 Back vertex distance values for nine subjects, measured five times with each device. The figure shows all individual results

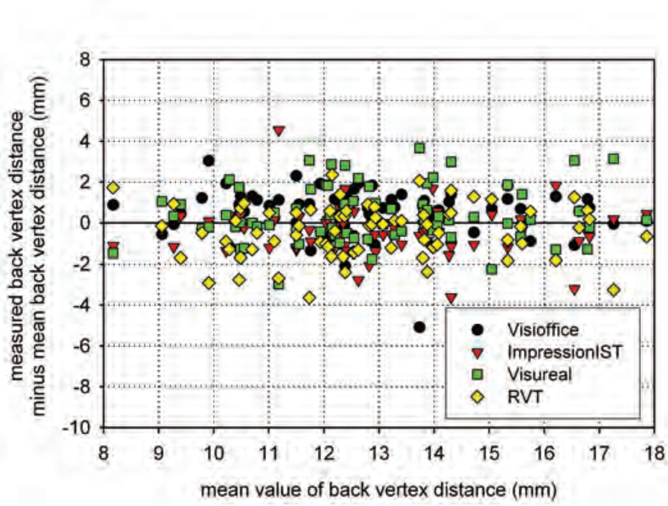


Figure 9 Bland-Altman diagram of the vertex distance (serial study)

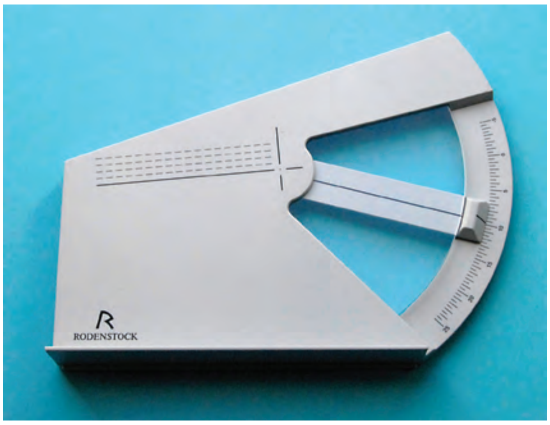


Figure 11 Tool for wrap angle measurements

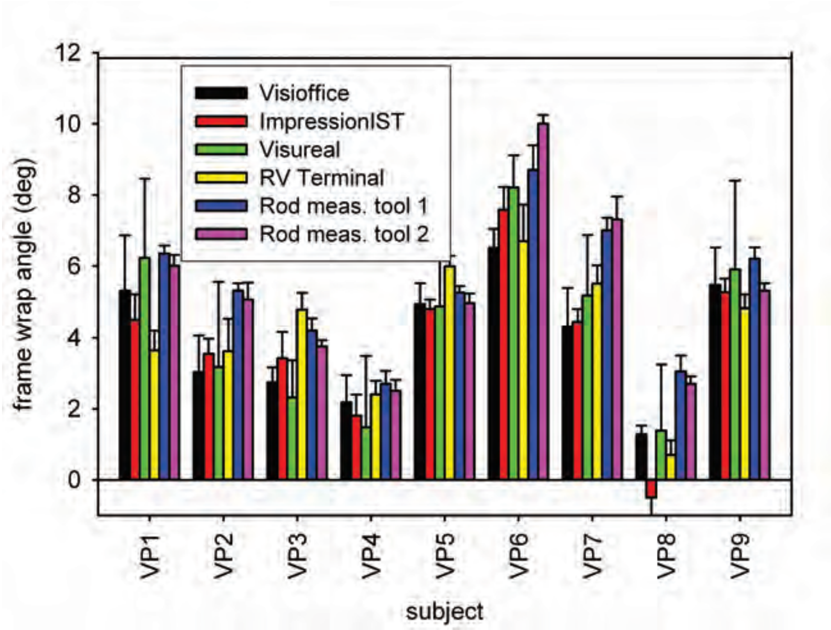


Figure 12 Frame wrap angle measured on nine subjects. Mean value and standard deviation were obtained from five individual measurements

Accuracy of measurement

During the present study, the pupillometers from 'Rodenstock'/ Buchmann and Topcon provided PD values that were smaller than the rest. In the study of Wesemann *et al* (1997)[7], a forerunner model of Topcon's device was tested and it also displayed PD values that were smaller than those of all other devices. If these two devices are excluded from the analysis, and if methodological differences are compensated for as described above, the user will obtain reliable PD values when using the other six devices.

Differences amount to less than ±0.3mm (Figure 5). In general, the accuracy of PD measurement was significantly better for video centration systems than for pupillometers. During the repeatability study, Essilor's Visioffice performed best (with σ = ±0.09mm). The corresponding values for pupillometers varied between σ = ±0.29mm and σ = ±0.47mm. In the study of Wesemann *et al* published in 1997, the standard deviation of four pupillometers was even larger and varied from σ = ±0.46mm to σ = ±0.63mm.

The accuracy of measurement of all devices under test in the present study is much better than the accuracy that can be obtained with a PD-ruler and Viktorin's method. Wesemann *et al* (1997) found a standard deviation of σ =±0.68mm and σ=±0.74mm with two different PD-rulers. A frighteningly large standard deviation of σ=±1.54mm was found in a recent study by Walsh and Pearce (2009).

One important aspect that was not investigated in this study is the influence of right and left rotations of head. In fact, we 'forced' the computer programs of all video centration devices to compensate for any kind of head rotation that was present at the time of measurement, although several subjects showed a marked head rotation when standing in front of the various devices. As far as our experience goes, right and left head rotations should be accounted for only when there is an important reason to do so (monocular vision, abnormal head posture etc).

Measurement parameters that depend not only upon the accuracy of the centration system, but also upon the subject's head and body posture, are found to be less precise than the PD. For those kind of centration parameters results strongly depend on how the subject is standing in front of the device during the measurement. Fitting point height and pantoscopic angle scatter much more than PD measurements. For all tested devices, standard deviation of fitting point height was approximately ±0.84mm. Standard deviation of pantoscopic angle values was approximately ± 2.0°. This was surprising, because it is technically easy to measure both parameters. Obviously, these measurement uncertainties are mainly caused by differences in the subject's head postures and, to a lesser extent, by measuring errors inherent in video centration systems.

Accuracy of measurement was also lower in vertex distance measurements as compared to PD measurements. Possible sources of errors include the following:

- As the measurement clip had to be placed onto the frame before every measurement and as the frame had to be put on afterwards, the frame fit was not exactly the same during the different measurements
- On some frames with stylish thick temples, the corneal apex was 'hidden' by the temple. Thus, an accurate adjustment of the measuring lines on the monitor was not possible.

Spectacle frame parameters

On three devices (Visioffice, ImpressionIST, RVT), the examiner is required to align the boxing lines with the border between lens and frame. On one device (Visureal), lines have to be adjusted to the position of the assumed groove bottom.

Both methods lack precision. When adjusting the lines with regard to the frame's border, the computer automatically adds an assumed standardised bevel depth for metal or plastic frames. However, the standardised depth was not identical to the 'true' bevel depth. When an adjustment is made based on the assumed groove bottom, an estimation error occurs. Overall, however, these errors are very small.

Influence of a high ametropia

All people with a high ametropia were excluded from our study. These patients see the fixation target or the mirror image of their face blurred. It can be expected that this will lead to fixation and measurement errors. Future research should be carried out in order to measure which fixation target (fixation light, laser-speckle-pattern, mirror image of the face) performs best ▶

on these problematic patients.

Natural head and body posture

The 'natural head and body posture' is and remains a key issue. Even our experienced subjects involved in the repeatability study had great difficulties in positioning themselves in front of the device. They were unable to adopt the same head posture during repeated measurements. This is probably the main cause of measuring errors.

Therefore, we recommend to transpose the measured fitting point height onto demo lenses in order to verify the measured results subjectively. This allows a detection of large measurement errors or an improper head and body posture during measurement.

Concluding remarks

All tested video-based centration systems measure data needed for personalised spectacle lenses in a single measurement session. This is less time-consuming than a measurement with pupillometer and additional measuring tools/gauges (for fitting height, wrap angle etc).

All tested video-based systems measure the PD to a higher precision than conventional pupillometers. The higher degree of accuracy alone, however, cannot completely justify the considerable higher purchase price. Conventional pupillometers and other mechanical centration tools also allow opticians a proper determination of other relevant centration data, provided that all due care is exercised.

To determine the general value of a video centration device, other benefits must be taken into account. Video centration devices present as 'point of sale' additional information on high-end spectacle lenses and personalised lens designs. The devices impress customers and promote sales of high-value lens products. Therefore, in addition to being a high-tech product, video centration devices also serve as a marketing and customer retention tool. And finally, working with them is a real pleasure.

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