UNIVERSITAT POLITÈCNICA DE CATALUNYA
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GRAU EN ÒPTICA I OPTOMETRIA

TREBALL FINAL DE GRAU

COMPARISON OF THE AMPLITUDE OF ACCOMMODATION MEASURED WITH A 3D SYSTEM OF VIRTUAL REALITY AND WITH CONVENTIONAL CLINICAL METHODS

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El Sr. Jaume Pujol i Sr. Mikel Aldaba, com a director i tutora del treball,

CERTIFIQUEN

Que el Sr. Ricardo Zurbano Casado ha realitzat sota la seva supervisió el treball *Comparison of the amplitude of accommodation measured with a 3d system of virtual reality and with conventional clinical methods* que es recull en aquesta memòria per optar al títol de grau en Òptica i Optometria.

I per a què consti, signem aquest certificat.

Sr. Jaume Pujol
Director del TFG

Sr. Mikel Alaba
Tutor del TFG

Terrassa, 25 de Gener de 2019

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TREBALL FINAL DE GRAU

COMPARACIÓ DE L'AMPLITUD D'ACOMODACIÓ MESURADES AMB UN SISTEMA 3D DE REALITAT VIRTUAL I AMB MÈTODES CLÍNICS CONVENCIONALS

RESUM

Aquest estudi compara l'amplitud d'acomodació proporcionada per una màquina de realitat virtual amb els mètodes convencionals de clínica Donders i Sheard.

L'estudi va incloure 25 subjectes sans (16 dones i 9 homes). L'edat mitjana ± desviació estàndard va ser de 24.28±5.86 anys. Es van excloure pacients amb trastorns o cirurgies oculars, hipermetropia latent i sense suficient rang d'acomodació.

L'amplitud d'acomodació es va mesurar al millor ull i sempre amb agudesa visual igual o superior a 20/20 Snellen. Primerament es va avaluar amb la màquina de realitat virtual i després al gabinet amb el mètode de Donders i el mètode de Sheard. Es van repetir immediatament les proves al gabinet per a 9 dels 25 pacients però la repetició de la màquina EVA per raons logística no va ser immediata.

A l'anàlisi estadística, el nivel de signifcació es va establir en p <0,05. Els diferents mètodes es van comparar mitjançant mesures aparellades (Donders-Sheard, Sheard-EVA i Donder-EVA), obtenint la diferència entre les dades i la diferència mitjana entre les dades per ser representats amb gràfics de Bland i Altman. Per avaluar la normalitat dels diferents mètodes es va procedir amb la prova Kolmogorov-Sminov, comprovant que no totes les variables tenien una distribució normal. A continuació es va utilitzar el test de Friedman per comprovar si hi havía diferències entre els tres mètodes, verificant que existíen diferències. Finalment es va procedir a l'anàlisi de Wilcoxon amb correcció de

Bonferroni per veure les diferències per parells de mètodes; identificant que existía diferències entre Donders-Sheard, Sheard-EVA però no entre Donders-EVA.

S'ha trobat que en la mesura de l'amplitud d'acomodació existeixen diferències entre els mètodes provats, encara que no s'han trobat diferències entre Donders i EVA. Els resultats obtinguts fan ser optimista respecte a la viabilitat del mètode basat en realitat virtual proporcionat per EVA en clínica.

RESUMEN

En este estudio se compara la amplitud de acomodación proporcionada por una máquina de realidad virtual con los métodos convencionales de clínica Donders y Sheard.

El estudio incluyó 25 sujetos sanos (16 mujeres y 9 hombres). La edad media ± desviación estándar fue de 24.28±5.86 años. Se excluyeron pacientes con trastornos o cirugías oculares, hipermetropía latente y sin suficiente rango de acomodación.

La amplitud de acomodación se midió en el mejor ojo y siempre con agudeza visual igual o mayor de 20/20 Snellen. Primeramente se evaluó en la máquina de realidad virtual y después en gabinete con el método de Donders y el método de Sheard. Se repitieron inmediatamente las pruebas en gabinete para 9 de los 25 pacientes pero la repetición de la máquina EVA por razones logística no fue inmediata.

En el análisis estadístico, la significancia se estableció en $p<0,05$. Se comparó los distintos métodos mediante mediciones pareadas (Donders-Sheard, Sheard-EVA y Donders-EVA), obteniendo la diferencia entre los datos y la diferencia media entre los datos para ser representados con gráficas de Bland & Altman. Para evaluar la normalidad de los diferentes métodos se procedió con la prueba Kolmogorov-Sminov, comprobando que no todas las variables tenían una distribución normal. A continuación se utilizó el test de Friedman para comprobar si existían diferencias entre los tres métodos, verificando que existían diferencias. Por último se procedió al análisis de Wilcoxon con corrección de Bonferroni para ver las diferencias por pares de métodos; identificando que existía diferencias entre Donders-Sheard, Sheard-EVA pero no entre Donders-EVA.

Se ha encontrado que en la medida de la amplitud de acomodación existen diferencias entre los métodos probados, aunque no se han encontrado diferencias entre Donders y EVA. Los resultados obtenidos hacen ser optimista respecto a la viabilidad del método basado en realidad virtual proporcionado por EVA en clínica.

ABSTRACT

This study, compared the amplitude of accommodation provided by a virtual reality machine with the classical clinical methods of Donders and Sheard.

The study included 25 healthy subjects (16 women and 9 men). The mean age ± standard deviation was 24.28±5.86 years. Patients with eye disorders or surgeries, latent hyperopia and without a sufficient range of accommodation were excluded.

The amplitude of the accommodation was measured in the best eye and always with visual acuity equal to or greater than 20/20 Snellen. First, it was evaluated in the virtual reality machine and then in the cabinet with the Donders and the Sheard method. The cabinet tests were repeated immediately in 9 of the 25 patients, but the repetition of the EVA machine for logistical reasons was not immediate.

In the statistical analysis, the significance was established at $p < 0.05$. The different methods were compared by pairs (Donders-Sheard, Sheard-EVA and Donder-EVA), obtaining the difference between the data and the average difference between the data to be represented by the Bland and Altman plots. To evaluate the normality of the different methods, we proceeded with the Kolmogorov-Sminov test, verifying that not all the variables had a normal distribution. Then the Friedman test was used to verify if there were differences between the three methods, checking that there were differences. Finally, we proceeded to Wilcoxon analysis with Bonferroni correction to see the differences by pairs of methods; identifying that there were differences between Donders-Sheard, Sheard-EVA but not between Donders-EVA.

It has been found that to the measure of the amplitude of accommodation there are differences between the tested methods, although no differences have been found between Donders and EVA. The results obtained make us optimistic about the feasibility of the virtual reality-based method provided by EVA in clinical practice.

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COMPARISON OF THE AMPLITUDE OF ACCOMMODATION MEASURED WITH A 3D SYSTEM OF VIRTUAL REALITY AND WITH CONVENTIONAL CLINICAL METHODS.

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Abstract

Purpose. This study, the amplitude of accommodation provided by a virtual reality machine is compared with the classical methods of the clinic Donders and Sheard.

The study included 25 healthy subjects (16 women and 9 men). The mean age ± standard deviation was 24.28±5.86 years. Patients with eye disorders or surgeries, latent hyperopia and without a sufficient range of accommodation were excluded.

Methods. The amplitude of the accommodation was measured in the best eye and always with visual acuity equal to or greater than 20/20 Snellen. First, it was evaluated in the virtual reality machine and then in the cabinet with the Donders method and the Sheard method. The cabinet tests were repeated immediately in 9 of the 25 patients, but the repetition of the EVA machine for logistical reasons was not immediate.

Results. In the statistical analysis, the significance was established at $p < 0.05$. The different methods were compared by pairs (Donders-Sheard, Sheard-EVA and Donder-EVA), obtaining the difference between the data and the average difference between the data to be represented by the Bland and Altman plots. To evaluate the normality of the different methods, we proceeded with the Kolmogorov-Sminov test, verifying that not all the variables had a normal distribution. Then the Friedman test was used to verify if there were differences between the three methods, checking that there were differences. Finally, we proceeded to Wilcoxon analysis with Bonferroni correction to see the differences by pairs of methods; identifying that there were differences between Donders-Sheard, Sheard-EVA but not between Donders-EVA.

Conclusions. It has been found that to the measure of the amplitude of accommodation there are differences between the tested methods, although no differences have been found between Donders and EVA. The results obtained make us optimistic about the feasibility of the virtual reality-based method provided by EVA in clinical practice.

Keywords: Visual System, Badal Optometre, Comparability.

Introduction

Accommodation is defined as the dioptric change in the power of the eye, which allows clear vision at different distances [1]. The light rays after passing through the cornea-tear medium converge in the crystalline lens that focuses the image on the photosensitive retina. The eye socket limits the eye ball, therefore, its focusing mechanism is not based on increasing or decreasing the distance between its dioptres, as a photographic camera would, instead, its focusing mechanism is based on the elasticity of the eye´s lens. When ciliary muscle tighten, zonular fibres slack, allowing the pliable crystalline lens to become more rounded to increase the power for close vision[2].

When an object is close the mechanism of convergence is activated and the visual axis angle is wider as the object gets closer. Convergence, pupillary constriction and accommodation are closely related, in the so called proximal triad. If accommodation is activated, miosis is induced; if convergence is activated, accommodation is induced; but miosis in and of itself does not generate convergence or accommodation.

In clinical practice, we can measure the ability of the visual system to change its power. When measured monocularly, the ability of the patient to increase the eye's dioptric value is measured, thus only the ability for contracting the ciliary muscle with their corresponding lens changes is evaluated. When performed binocularly, the ability of the accommodative system to respond in the presence of convergence is also measured. The amplitude of accommodation (AA) measures the maximum capacity that the lens has to focus expressed in dioptres.

With age there is a loss of AA, this begins at the age of 10 becomes significant approximately at the age of 45 and is known as presbyopia. At this age, an emmetropic eye needs positive addition to compensate the gradual loss of accommodation. Depending on the degree of myopia, the appearance of symptoms in close vision will be delayed, as these patients have good vision for close distances without need of accommodation. In hyperopia, accommodation plays a key role because young patients with a long range of AA compensate the lack of refractive power by means of accommodation. These patients will have latent hyperopia until it becomes apparent with time.

Another important change that lens undergoes with age is the loss of transparency. After the age of 60, the perfectly grouped proteins of the lens are denatured and ungrouped due to the increasing accumulation of waste metabolites. They regroup again, this time out of order, creating opaque zones where the incident light disperses, preventing clear vision at any distance; this is the beginning of cataract[3]. Not only aging, but also any pathology, medications and even trauma that affect the good function of the fibres can cause the onset of the cataract. Currently, surgery is the only solution to the symptoms derived from cataract, and it involves the removal of the natural lens and the implant of an artificial one.

There are certain conditions in which accommodation is impaired. The accommodative dysfunctions are accommodative insufficiency, accommodative infacility, ill-sustained accommodation, paralysis of accommodation and spasm of accommodation. Accommodative insufficiency takes places when the AA is two dioptres below what is expected based on patient´s age. Accommodative infacility is a condition in which there is difficulty in changing the accommodative state from one fixation distance to another. Ill-sustained accommodation is similar to accommodative insufficiency, except that the accommodative power is normal, the patient has blurred vision after prolonged near work. It occurs because the accommodative system fails to sustain long-term accommodative effort. Paralysis of accommodation results when a non-presbyopic patient loses the ability to accommodate either monocularly or binocularly. The chief complaint is blur due to failure to accommodate. Spasm of accommodation occurs when the accommodative system inappropriately over accommodates for a stimulus. It is also known as spam of near reflex, because it is related to the effort of the triad (accommodation, convergence and miosis). The overstimulation of the parasympathetic system in continuous close-up tasks, without visual hygiene causes the paralysis of ciliary muscles, the muscle is not able to relax to its maximum extent and causes pseudomyopia in distant vision. The most common causes are psychological, others are due to the use of cholinergic drugs, traumatisms, cranial tumours and myasthenia. [4] [5] [6]

There are two ways to measure AA in clinical practice, in a subjective way and in an objective way. The subjective methods are those that require a participation or response from the patient, while in the objective methods there is no patient intervention.

Among the most common subjective methods to measure AA, there is the Donders' method (approaches), and the Sheard method (adding negative lenses). Both methods can be performed monocularly or binocularly. The Donders' method overestimates values since the visual angle of the stimulus enlarges as it gets closer to the eye; the opposite is true in Sheard's method, where the visual angle of the stimulus is increasingly smaller. Both Donders and Sheard's methods were used in this work and their application is detailed in the methodology part.

Another subjective method for measuring accommodation are the Jackson's cross-cylinders (equivalent ±0,50D orientated to 90º), that measures the accommodative response to a stimulus. It is based on the fact that the eye accommodates as little as possible because of its depth of field (dioptric range of the visual system where no blurring is perceived) [6]. The stimulus is a fixation card with vertical and horizontal lines at a certain distance (usually 40 cm). The patient can have three potential answers: 1) Both lines are seen equally, the accommodative delay is zero. 2) The patient observes the horizontal lines sharper than vertical ones, there is a lag of accommodation, and adding positive lenses both lines will be perceived equally clear. 3) The patient can see the vertical lines sharper, there is a lead of accommodation, and adding negative lenses will cause similar perception of the horizontal and vertical lines.

There is also an indirect subjective method to measure accommodation, it is the next point of convergence. It is a binocular measure in which a stimulus is approached by measuring the point of rupture (double vision) and the recovery point (fusion) of the simple image by moving the stimulus away. It is therefore a direct method to measure the closest point in convergence where there is simple vision. As the convergence draws the accommodation (also the miosis), the maximum accommodation is indirectly measured binocularly. When high values of double vision perception are reported, it would be necessary to evaluate whether convergence or adaptation is what fails.

Objective measures for accommodation include the Nott retinoscopy and Mem retinoscopy tests, both binocular. The accommodative response is not found where the stimulus is, so in a objet located at 40 cm, the normal answer is about 2,0 dioptre instead of 2.5 dioptres (a lag of accommodation of 0.5 dioptres). With the Nott method, a near point of visual acuity (VA) 0.5-0.6 at 40 cm is used with a window in the card by which the optometrist locates the streak of the retinoscopy and neutralizes the direct movement, moving away. However, when the movement is inverse, that is, when the accommodative response is greater than the accommodative stimulus, this method is not valid and the method of Mem has to be used. In this method we take advantage of the phoropter's lenses, the object is fixed in the retinoscope, located at 40 cm from the patient, using positive spherical lenses to neutralize the direct reflection and negative spherical lenses for the reverse movement. [6]

The autorefractometers are an alternative to the retinoscopy. They can be based on different principles, being the Scheiner's disc one of the most popular. A new generation of autorefractometers is based on aberrometry and mainly in the Shack-Harmann wavefront sensor. In short, it consists of an array of microlenses that enables the measurement of wavefront aberrations. The aberrated images obtained through the array of microlenses are captured in a charge-coupled device camera and then are compared with the ideal images of an optical system without aberrations created by a perfect wave front. From the displacement of the recorded image relative to the reference (ideal) image, the wavefront can be reconstructed. The calculated aberrations can be then used to determine the spherical and cylindrical refractive state of the patient.

The autorefractometers usually include a Badal system to stimulate accommodation. The Badal optometer is based on the change in the relative distance from an objecto to a lens in order to accomplish the desired vergence at the output of this optical system. The Badal system has two main advantages. Firstly, it allows a change of vergence without modifying the planes conjugated with the pupil. Secondly, it allows a linear relationship between the introduced vergence and the distance variation between lenses. [7]

There is ccurrently a growing interest in the use of virtual reality (VR) equipment, as it has high clinical potential. Equipment, such as EVA (Eye Visual Analyzer), developed in the Terrassa CD6 (Centre for Sensors, Instruments and Systems Development), Universitat Politècnica de Catalunya is nowadays available. EVA is composed of optical modules with a double eye tracker of 12 infrared-light emitting diode (IR LED) that monitor the position of both eyes during all tests. It is equipped with a Shack-Harmann wavefront sensor that gives an objective refraction.

The fixation test is based on a display seen through a variable focus system. For subjective refraction, EVA applies its own algorithm that resembles the conventional clinical method based on maximum plus to maximum VA.

In Eva, AA´s test relies on Sheard´s test, using an electro-optical lens. This lens consists of a liquid element covered by an elastic membrane. When voltage is applied to the lens, the curvature of the surface changes, thus modifying the spherical power of the lens. Although EVA is increasing the negative power with the electro-optical lens, because EVA has an optical Badal system, there is no minification of the final image that the patient perceives. As previously explained, these are optical systems that induce vergence without changing the magnifications. In other words, they simulate different distances to the observed object, without changing its size.

This VR equipment presents some problems that indicate that the accommodative response is different in real conditions than in virtual conditions. The difference may be explained by the effect of other factors such as the field of view or the depth of the stimulus, rather than the method to stimulate accommodation. [8] Otero reports that under particular conditions in the virtual system, we can achieve a quality stimulation: using a 2- dimensional stimulus with apparent depth cues and simulated out-of-focus blur in a relatively large field of view that gives an optimum peripheral retinal image size.

Our study's objective is to compare the measure of the AA in the VR system with the reference subjective that is the AA in natural conditions.

2. Equipment and methods

2.1 Subjects.

The study conducted at Davalor Research Centre (DRC) (Terrassa, Spain) included 25 healthy patients, (16 women and 9 men). Criteria for inclusion was best spectacle-corrected VA of 20/20 Snellen in the best eye or better, and no history of any ocular condition, surgery and/or pharmacological treatment. Patients with latent hypermetropia and without a sufficient range of accommodation were excluded. Personal data for all subjects was registered; all participants were informed of the organic law 15/1999 of December 13 about Protection of Personal Data (LOPD). The study followed the tenets of the Declaration of Helsinki, and all participants gave their informed written consent. The lower age limit was set at 12 years old and the upper age limit was set at 38 years old to help ensure enough AA.

2.2. Equipment.

A virtual reality machine EVA and a conventional cabinet were used.

EVA is a new machine for assessment, diagnosis and therapy of visual function. EVA introduces the patient to a world of 3D virtual reality. EVA has two displays (one for each eye) where the virtual image is perceived with depth, so that the user's vision courses with vergence and simultaneous accommodation to the different distances in depth of the stimuli [9]. EVA analyses the binocular vision in record breaking time and creates a visual, personalized, fast and playful therapy if need be. All of this takes place through a virtual game based on characters from the Mayan culture, in which each of the necessary clinical protocols is camouflaged. Some of the exams do not require the engagement of the patient, others demand the patient's involvement through a keypad located on the side of the armrest of the seat.

Designed by a multidisciplinary team, from electrooptic specialists, mechanical software developers to optometrists, this project is promoted by the company

DAVALOR SALUD and the CD6 from Universitat Politècnica de Catalunya, as a research partner.

EVA contains a head inside which has the different optical modules that are able to explore and record up to 75 clinical parameters of visual function at all times. The stimulus is always VR and the eye movements are recorded through the dark-pupil based eye-tracker with twelve IR LEDs that act like a spot light while remaining invisible to the naked eye. [10]. To obtain the refraction of the patient EVA uses a Hartmann-Shack autorefractometer, and the AA is obtained through the Sheard method, adding negative power, thanks to the electro-optical lens of its optical module while the patient visualizes a Mayan soldier as a stimulus in a VR environment.

In addition to EVA, conventional clinical practice material consisting of an open field WHAM-5500 autorefractometer was also used, with a black Maltese cross, as a fixation target located at 6 meters and phoropter with a fixation objective rod consisting of AV 18/20 test placed at 40 cm.

2.3 Experimental Protocol.

Firstly, personal data was collected and the LOPD was signed by the patient. The patient then moved on to EVA.

Prior to the start of each test, a calibration of the machine was required. After taking the height of the patient by means of a laser from the head, the patient was able to take a seat, he or she would self-adjust depth and height to an ergonomic position. After the head was lowered and after scanning the physiognomy of the patient's head, the optical modules were fitted and calibrated for each eye, at which time the eye tracker was activated and the virtual game began with each of the visual demand tests that listed below:

1) Autorefraction: Based on objective refraction with a Harmman Shack while the patient looks at a house in the background with a road and different elements to simulate distant distances though a display.

2) VA captures of each eye: In the centre of the display, there´s an image of a dice with the E of Snellen on each side that spins until it stops. The four possible orientations of the E appear in each of the four corners of the screen. The patient chooses with the movement of his or her eye the orientation he or she believes he or she sees on the visible front face of the dice. This way, the eye tracker receives the response. The initial stimulus is below the VA threshold, specifically 0.3logMAR, and increases progressively with a constant rate until the patient can identify the stimulus. The stimulus is presented several times until the response to the VA is set by the limits method.[9]
3) Subjective refraction with Davalor's algorithm, which is similar but not identical to the subjective refraction test in cabinet when obtaining the maximum positive sphere and the minimum negative cylinder that provides the best VA. [10]
4) The Covert Test in far vision and near vision consists of unilateral occlusion about 5 seconds in length per eye. During the test the patient keeps his glance fixed in a virtual rotating ball with two faces, white and black. In order not to distract attention from the fixation point (the ball), the patient is asked to pause the ball on the white face with the bottom located on the side of the EVA seat.
5) Near Point of Convergence (NPC), binocularity, the Mayan king of the virtual game approaches the display until the patient presses the button panel when perceiving double vision and then presses again when perceiving simple vision.
6) AA by Sheard's method: As previously mentioned, one of the Mayan characters of the game, particularly, a soldier is presented as a stimulus. The soldier is a colour real 3D graphic, with no information of the minimum detail and its size remains constant thanks to the Badal System. A voiceover in the videogame asks the patient to look at the stimulus and press the button when the patient sees blurry. The electro-optical lens of the cartridge increases the negative power, not in fixed increments of 0.25 D as in a conventional phoropter, but progressively and constantly. The

result that EVA shows is the closest value to a quarter of a dioptre, so for instance, if the patient had pressed the bottom when the total power was, for instance -6.120 D, then the value provided would be 6.00D.

In addition to these tests, EVA has the capability of testing horizontal-vertical reserves, flexibility of vergence and accommodation flexibility when detecting forias and accommodation ranges outside of normality. In any of the 25 patients, such tests were needed.

After the EVA test set, the patient was taken to a conventional cabinet where the following protocol was followed:

1) Objective refraction measurement with open field autorefractometer WHAM-5500 with a black maltase cross as a stimulus placed at 6 meters.
2) Monocular subjective refraction in phoropter of both eyes by the positive maximum sphere method and the negative cylinder minimum that provides the best VA.
3) VA measurement in both far vision and near vision.
4) AA determined by the Donders method only in the eye with best VA, and with the same VA in both eyes only in the dominant eye. The Snellen VA 18/20 test was performed in a phoropter rod from 40 cm until the patient indicated blurred image.
5) AA by Sheard's method, with Snellen test of AV 18/20 at 40 cm. Negative power was increased in steps of -0.25D only in the best eye until the patient indicated blurring.

In both the EVA and the cabinet, the luminous flux per unit area was calculated with a luxometer, IL-1700. EVA´s illuminance was 3,27 lux and cabinet´s illuminance was 6,00 lux. The same lighting conditions were maintained during all tests for both systems.

2.4 Statistical analysis.

Statistical analysis was performed using IBM SPSS Statistics 24 (IBM; Armork, NY). Statistical analysis is divided into different parts. Firstly, a descriptive statistic was made, showing the means and standard deviations of the different variables studied. The differences between methods for measuring AA using the Bland & Altman plot were then studied. After checking the normality of the samples, a statistical analysis was carried out with the corresponding method, and finally the repeatability was studied.

In descriptive statistics, for the four techniques used to measure AA (EVA, Donders, Sheard and Hofstetter), their corresponding means, standard deviation and the minimum and maximum ranges are showed.

The results obtained were matched creating three Bland & Altman plots. The Bland-Altman plot or difference graph, is a graphical method to compare two measuring techniques (A-B). A scatter plot is shown with the differences between the two measuring techniques versus the averages of both. It is a statistical resource to determine if two clinical methods of measuring could be used interchangeably. Y axis shows the difference between the two paired measurements (A-B) and X axis represents the average of these measures ((A+B)/2). In other words, the difference between the two paired measurements is plotted against the mean of the two measurements. In the plot the central line represents the mean differences between two methods, the dashed lines represent the lower and upper of 95% limits of agreement computed as the mean difference ±1,96*standard deviation of the differences. [11]

To evaluate the normality of the different methods, we proceeded with the Kolmogorov-Smirnov analysis, concluding that not all variables had a normal distribution and, therefore, a non-parametric analysis was performed. There are more than two samples: EVA, Donders and Sheard, and because it´s non-parametric, its corresponding statistic is the Friedman test. With the Friedman test, the three samples were checked at the same time, verifying that there were differences between the samples. We proceeded with a Post-hoc analysis of

Wilcoxon and a Bonferroni [12] correction to find the differences by pair methods.

In the repeatability analysis, the Within-subject Standard Desviation test was used and the repeatability values (Sw) were obtained for each of the AA techniques assessed.

3. Results

The mean age ± standard deviation (SD) was 24.28±5.86 years (range from 12 to 38 years). The average sphere in cabinet and in EVA were -0.49±1,81 dioptres (D) (range from -6.00 to 4.25D) and -0.43±1.88D (range from -6.25 to 4.50D) respectively. The average cylinder ±SD in cabinet and in EVA were -0.87±1.35 D (range -5.00D –0.25D) and -1.10±1.32 D (range -4.50D – -0.25D) respectively.

The descriptive data (mean, SD and ranges) for the four managed methods (AA EVA, AA Donders, AA Sheard, AA Hofstetter,) are shown in table 1.

	Mean	SD	Ranges
AA EVA (D)	8.92	3.15	[3.00-18.25]
AA Donders (D)	8.31	2.62	[4.34-16.66]
AA Sheard (D)	6.97	1.72	[4.00-11.50]
AA Hofstetter (D)	11.22	1.76	[7.10-14.90]

Table 1. Descriptive statistics table. Mean, SD and ranges of different AA.

Figure 1 compares the measuring technique of the AA with Donders against that of Sheard (figure 1), both obtained in the cabinet. In this comparison, there was an average value of the difference of 1.33 D and the upper and lower agreement limits for the 95% of the sample, were 5.76 D and -3.10 D.

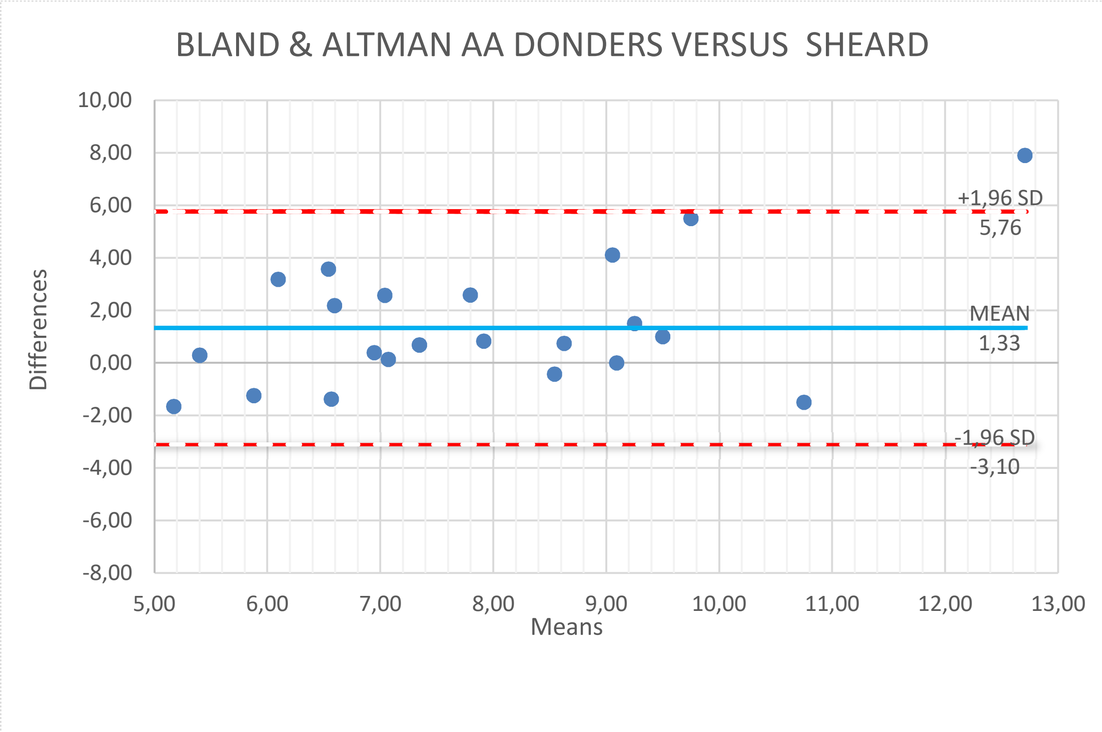

*Figure 1. Bland and Altman plots showing the differences between the measurements of AA between Donders and Sheard in cabinet. The solid blue line represents the mean differences between two methods, 1.33. The red dashed lines represent the lower -3.10 and upper 5.76. 95% limits of agreement computed as the mean difference ±1.96*standard deviation of the differences.*

In the comparison between the AA technique of Sheard in the cabinet against the AA of the EVA machine (figure 2), the average value of the difference between the data obtained by the two methods was -1.95D and the upper and lower agreement limits for the 95% of the sample, were 3.04D and -6.94D.

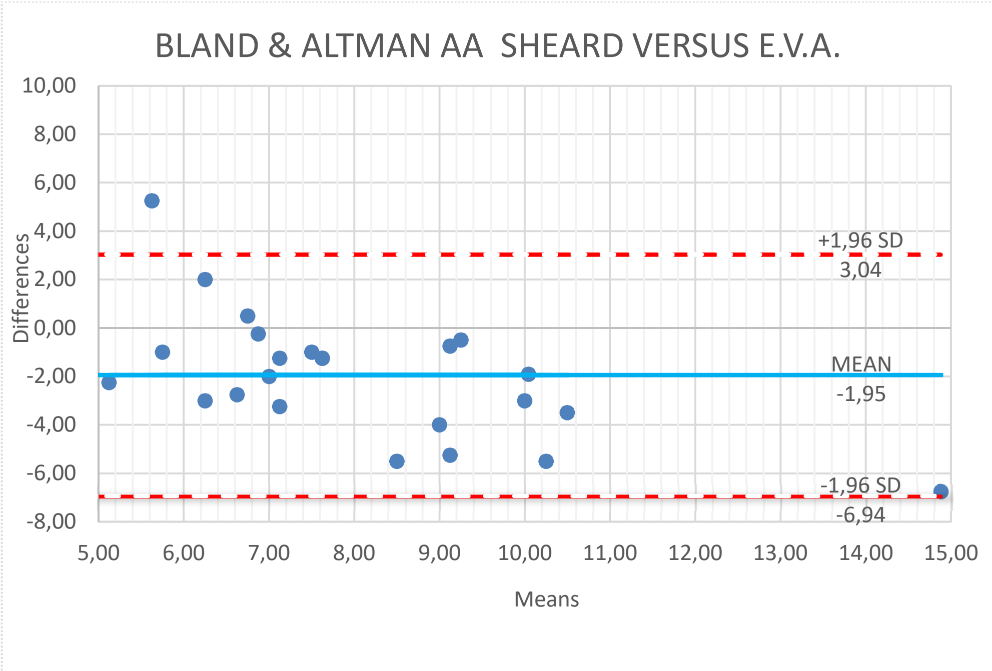

*Figure 2 Bland and Altman plots showing the differences between the measurements of AA between EVA and Sheard. The solid blue line represents the mean differences between two methods, -1.95. The red dashed lines represent the lower -6.94 and upper 3.04. 95% limits of agreement computed as the mean difference ±1.96*standard deviation of the differences.*

Finally, figure 3 shows the graph of Bland and Altman comparing the technique of Donders in the cabinet with the technique used by EVA for the measurement of the AA with an average value of the differences of -0.61, 95D and the upper and lower agreement limits for the 95% of the sample, -7.29D and 6.06D.

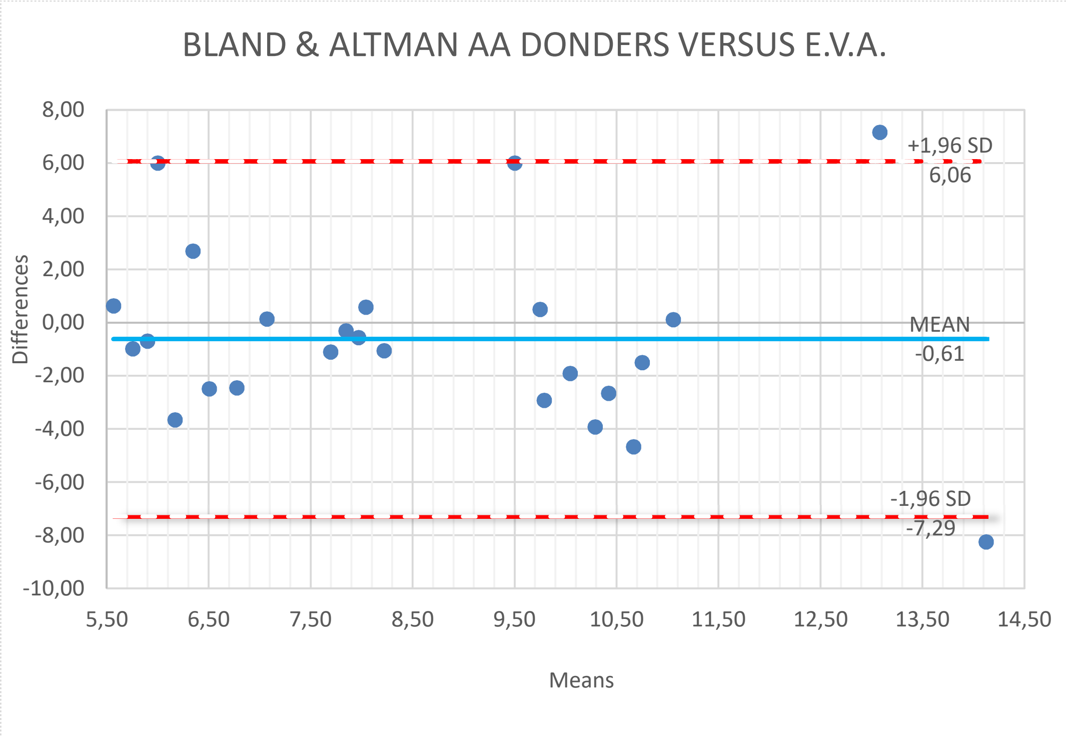

*Figure 3 Bland and Altman plots showing the differences between the measurements of AA between Donders and EVA. The solid blue line represents the mean differences between two methods, -0.61. The red dashed lines represent the lower -7.29 and upper 6.06. 95% limits of agreement computed as the mean difference ±1.96*standard deviation of the differences.*

As previously shown in the statistic analysis, we first proceeded to study the normality of the samples, in order to do so, the Kolmogorov-Smirnov test was used, with a significance of p <0.05. The results can be found in table 2 for each of the techniques used. As it can be observed in all cases, a p> 0.05 was obtained, therefore the distributions are not normal (table 2).

	Kolmogorov-Smirnov		
	Statistical	gl	Sig.
AA DONDERS	,143	25	,200
AA E.V.A.	,144	25	,191
AA SHEARD	,134	25	,200

Table 2. Statistic results of Kolmogorov-Smirnov and Shapiro-Wilk test for normality.

As a result of the variables not having a normal distribution, a nonparametric analysis of variance and multiple comparisons on ranks was carried out with Friedman test. (table 3)

Friedman test	
N	25
Chi-cuadrado	18,323
gl	2
Sig. asintótica	,000

Table 3. Statistical results of Friedman test for multiple comparison.

Having a value p<0.05 indicates that there are differences amongst the different methods that were used; Donders, Sheard and EVA. A Post-hoc analysis of Wilcoxon (table 4) is performed to know the differences between pairs of techniques. A Bonferroni correction is applied to the result taking into account the number of possible combinations.

Correction of Bonferroni

	SHEARD - DONDERS	E.V.A. - SHEARD	E.V.A. - DONDERS
Sig. asintótica (bilateral)	,030	,003	,384

Table 4.Correction of Bonferroni.

Repeatability was studied with the Within-subject Standard Deviation test and repeatability values (Sw) of ±0.29D were obtained for Donders, ±0.19D for Sheard and ±0.37D for EVA. It is that in the study of repeatability, if a lower value from Sw is obtained, this means the repeated measures are more similar to each other and consequently more precise. Therefore, Sheard is first found as the technique with the highest repeatability, followed by Donders and finally by EVA.

4. Conclusions

The study of AA is a tool of great practical interest because it is fundamentally related to presbyopia and accommodative dysfunctions that can affect the patient's visual health. There are different methods to measure AA and, nowadays the use of new technology such as virtual reality is gaining importance. Although they have not yet been introduced in clinical practice, in recent times, systems based on new technologies have been proposed to develop optometric tests, such EVA made in Davalor's company. This is why, in our study, we wanted to compare the traditional methods of measuring AA (Sheard and Donders) with those proposed by the new virtual reality system, EVA.

The mean values of AA found in the analysed population are below those presented by the Hofstetter´s AA average formula. This fact may lead us to suspect that the population used has a tendency to a lower mean of AA than the general population. However, there is a large amount of literature that reveals average AA data examined and that which do~~es~~ not correspond to those which could be predicted by the Hofstetter´s formulas. Jaclyn A Benzoni and Mark Rosenfield point out that Hofstetter's formulas, based on the AA studies of Donders and Duane, have worse predictability as, the population analysed, approaches the paediatric age group. This is due to the fact that Donders did not examine subjects under 10 years of age and Duane, from the 1500 subjects examined between 8 and 72 years of age, there was only one group of 33 subjects between 8 and 12 years old [13]. Other authors discard the linear progression in the loss of AA with the age described by the Hofstetter´s formulas, and propose a curvilinear decreasing progression between 3 and 40 years of age that, combined with the data of other previous studies, give a sigmoidal function that describes the general tendency to the loss of AA during life, with a greater progression between 20 and 50 years[14].
The comparison of the different methods to measure AA (Donders, Sheard and EVA) shows statistically significant differences between the three. In the comparison by pairs, comparing Sheard with Donders we have a mean difference of 1.33D with 95% intervals from 5.76D to -3.10D. We also found differences

between Sheard and EVA; with means of difference of -1.95D with 95% intervals from 3.04D to -6.94D. However, in the comparison, EVA with Donders differences are not statistically significant. These discrepancies may be for various reasons. The refraction used by EVA (starting point of the AA) and in the cabinet was discarded as the cause of the differences, since both measurements were very similar, obtaining a spherical equivalent in EVA of -0.72 D ± 1.87 SD and a spherical cabinet equivalent of -0.79D ± 1.75 SD, with an average difference of 0.07D.

We found a significant difference between the methods used in regards with the increase in the visual angle of the test presented during the measurement of the AA. In Sheard, a minimization of the stimulus occurs as we increase the negative power. On the other hand, in EVA, the stimulus remains constant because there is an optical Badal system. In EVA, the patient's entrance pupil is in the focal image of his Badal optical system and, therefore, the visual angle is always the same. And in the case of Donders, there is a magnification of the stimulus by the approach of the eye chart. The minimization of the stimulus in Sheard, by adding negative lenses, makes the task more difficult for the observer and therefore lower values of AA are obtained, in comparison with other methods where there is no minimization, such as EVA or, in methods such as Donders, where there is also magnification. These differences between methods could explain, in part, the differences found in the measures.

There are other differences between the different methods to measure AA that can explain the disagreements found, such as the lighting used or the fact of presenting real stimuli or virtual stimuli in a virtual reality environment. This could cause differences in the measurement result of AA, mainly due to the interposition of objects in the depth of view and in the field of view [15].

Illumination restricts the pupil diameter which determines the depth of focus and it can therefore influence the AA. In our case, we have to take into account that the lighting of the cabinet and EVA was, as far as possible balanced. Because in EVA the illuminance could not be adjusted, the light source was minimized in the cabinet. As we have mentioned before, the illuminance in EVA was 3.27 lux, so in the cabinet it was necessary to work with a lower illuminance than usual in close vision tests, such as accommodation. To approach the EVA illuminance, the cabinet´s near source light was not used, but the ambient light, with a final illuminance value of 6 lux. Although there is a small difference in illuminance between the cabinet and EVA that would cause slight differences in the size of the pupillary diameter, this would not be enough to justify the differences in the measurement of the in both situations. Therefore, we believe that it is not a factor of maximum importance.

Another factor that could explain the differences in the AA measure is the spatial reference or the interposition of objects in depth. In the measurement of the AA, EVA works in a closed environment where there is no real spatial reference, whereas Donders and Sheard work in the cabinet, in an open environment where there are real spatial references. Rosenfield indicates that proximity cues improve the stimulation of accommodation [16] and Otero et al. demonstrated that in virtual reality environments, the interposition of objects in depth is a key factor to have a good accommodative response [8]. Thus, in the cabinet we are faced with an environment where there is spatial information in the peripheral scene (distances) that helps a better accommodative response. In contrast, in virtual reality environments, the patient observes a plan in two dimensions where spatial references are lost. In EVA, although there is no spatial information in different focal planes, it tries to solve this deficiency by image processing, presenting objects at different planes (Mayan indian and background) and defocusing one in respect to the other (digitally). Although it has been demonstrated that this processing of the images [8] helps a better accommodative response, in the case of EVA, spatial information is scarce, which could explain, in part, the differences in the measured AA.

On the other hand, Aldaba et al. [15] suggest that the size of the field of vision could be an important factor in controlling and providing accurate accommodative responses. Recent studies by Carles Otero [8] indicate that for a stimulus of

2.50D, that is, a reading task, the accuracy of the accommodative response was better when moving from an objective field of vision of 2.5º to 10º, but there were no differences going from 10º to 30º. In EVA, the field of view is smaller than in the cabinet. That might suggest the limitation in the accommodative response. However, the field is greater than 10º, which as we have seen, is enough to achieve a response equivalent to that of a broad field (30º). Thus, any effect of the field of view on the differences found in the AA measure is discarded.

Higher repeatability values were found in EVA than in cabinet, with Sheard's repeatability being the best. In relation to repeatability, it must be mentioned that although EVA obtained worse values, it had an added handicap. In the repeatability of EVA, for logistical reasons there was a greater time lag between the repetition of the tests than in the case of Donders and Sheard, where the repetitions were practically immediate. Thus, the greatest difference between repetitions for the EVA case may be partly due to this reason.

The purpose of our study was to measure the AA in a virtual system like EVA and compare it with more classical methods. We have seen that there are differences between the different methods, but we also observe that, in this incipient technology, discrepancies are not huge. Especially, if data is compared with Donders. We believe that if this was to be implemented in clinical practice, a series of parameters should be ameliorated, such as the type of stimulus, or trying to improve the conditions of the target, as proposed by Otero. Even so, we believe that, in the near future, this technology can be applied and be of great clinical utility.

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