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Theoretical Effect of Coma and Spherical Aberrations Translation on Refractive Error and Higher Order Aberrations

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Abstract: (1) Background: The purpose of the study is to present a simple theoretical account of the effect of translation of coma and spherical aberrations (SA) on refractive error and higher order aberrations. (2) Methods: A computer software algorithm was implemented based on previously published methods. The effect of translation (0 to +1 mm) was analyzed for SA (0 to +2 µm) and coma (0 to +2 µm) for a circular pupil of 6 mm, without any rotation or scaling effect. The relationship amongst Zernike representations of various aberrations was analyzed under the influence of translation. (3) Results: The translation of +0.40 µm of SA (C[4,0]) by +0.25 mm with a pupil diameter of 6 mm resulted in induction of tilt (C[1,1]), −0.03D defocus (C[2,0]), +0.03D astigmatism (C[2,2]) and +0.21 µm coma (C[3,1]). The translation of +0.4 µm of coma (C[3,1]) by +0.25 mm with a pupil diameter of 6 mm resulted in induction of tilt (C[1,1]), −0.13D defocus (C[2,0]) and +0.13D astigmatism (C[2,2]). A theoretical quantitative relationship between SA, coma, astigmatism and defocus is presented under the influence of translation. (4) Conclusion: The results can act as a guide for the clinician, in order to readily assess theoretical impact of wavefront map translation from pupil center to the visual axis. The resultant refractive coupling has to be taken into consideration especially when treating eyes with an abnormal corneal shape and/or large pupil center to corneal vertex chord.

Keywords: spherical aberrations; coma; astigmatism; scaling; translation; Zernike polynomials; keratoconus; ablation centration; offset; relationship between aberrations

1. Introduction

The human eye is an optical system comprising four main non coaxial optical elements. Although, the optical surfaces are aligned almost co-axially, the deviations from a perfect optical alignment results in a range of optical and neural axes and their inter relationships. Besides the optical axes, the sharpest vision of a target is realized when it is in line with the fixation target and the fovea of the retina (called the visual axis). Due to the discrepancy between the optical center (projection of the optical axis on the retina) and the visual center (which corresponds to the fovea), there exists a debate among clinicians in the refractive community about the choices made in the corrective strategy; whether the correction provided should maximize the quality of the wavefront at the fovea or whether it should focus on an overall improvement of the optical system.

The optical quality of human eyes is often described in terms of wavefront aberrations [1]. Many commercial devices are now available to assess with reasonable accuracy the distribution and contribution of each aberration to the overall wavefront map in the individual eye, albeit with some disagreement amongst various commercial systems [2,3]. Wavefront measurement techniques and the driven refractive procedures are often designed based on the expansion of Zernike polynomials [4]. The statistical properties of Zernike expansion have been determined in different studies [5–7]. While low-order aberrations, defocus and astigmatism, are the predominant terms in normal human population, third-order aberrations (coma and trefoil) and spherical aberrations (SA) are the most predominant higher order aberration (HOA) and may represent around 6% and 2%, respectively, of the total wave-aberration variance [8,9]. The relative amounts of aberrations in groups of normal eyes have been found to be similar in different studies [10], but the type and nature of the correlation between them is still a debatable issue [11].

The pupil center (PC) to corneal vertex (CV, estimated through the coaxially sighted corneal light reflex) offset has been reported to be under 0.5 mm in various studies assessing normal subjects [12]. This translational offset can affect the treatment of aberrations under several clinical scenarios. Controversial opinions exist concerning the centration of the ablation profile in refractive surgery, with The Subject-Fixated Non-Coaxially Sighted Corneal Light Reflex (SF-CSCLR) [13] and PC-oriented procedures forming the majority. The aberrations generated by the offset (which varies according to the individual and the pathologies treated) from the optical axis provides an objective decision element to tackle this controversy.

Although, the ideal location to maximize visual outcome is yet to be determined, SF-CSCLR [13] is preferred over PC refractive procedures. The HOAs are aligned to the Line of Sight and are closely approximated by the PC. On the other hand, the manifest refraction values are aligned to the visual axis and are closely approximated by the CV. Since lower order aberrations (sphere and cylinder) form the dominant aberrations in normal human eyes, a translational offset from the PC to the CV is often realized in the form of a symmetric offset in ablation profiles in corneal wavefront-guided (CWG) treatments, resulting in translation in PC centered HOAs. CWG ablation profiles have also been developed to combine HOAs referred to PC with manifest refraction values referred to CV by inducing an asymmetric offset [14]. For topography-guided refractive procedures, both refraction and topography are derived with a reference to CV. Most commercial topographers explain the abnormality in the topography in terms of HOAs. If these HOAs are manipulated in a refractive procedure with CV centration, a surgeon should also observe the PC-centered HOAs using an aberrometer, in order to understand how much refractive coupling will be produced in the cornea. In the exclusive case where an ocular wavefront-guided (OWG) treatment is performed on the cornea with pupil centration, the impact of translation in pupil-centered HOA with respect to the CV can be neglected. This is valid given the ocular wavefront (OW) is taken as is, i.e., low order aberrations (LOA) and HOA are not manipulated. From the moment that the LOA are manipulated (based on nomogram, manifest refraction, target refraction) the difference between OW LOA and planned LOA will induce coma and trefoil (even in the ideal case that no SA is induced). In any of the above-mentioned clinical scenarios, one must estimate the impact of PC centered HOAs on manifest refraction, ablation centration and post-operative outcomes.

The effect of possible interactions of aberrations like astigmatism and coma has been presented in many studies [15]. The addition of increasing amounts of aberrations reduces the subjective vision, with defocus, SA and secondary SA being the most degrading aberrations [16]. To predict corneal pseudo-accommodation, the most important Zernike term is SA in normal eyes and coma in eyes with prior laser corneal surgery [17,18]. The majority of the visual impact of high levels of fourth-order Zernike aberrations can be attributed to the second-order terms within the Zernike polynomials. Therefore, the impact of SA can be minimized by balancing it with a defocus term that flattens the central wavefront (paraxial focus) or maximizes the area of the pupil with a flat wavefront [19]. Vinas M et al. [16] measured the Visual acuity in 25 subjects (astigmatic and non-astigmatic, corrected and uncorrected) under induction of astigmatism and combinations of astigmatism and coma while controlling subject aberrations. They found that the impact of astigmatism on visual acuity is greatly dependent on the orientation of the induced astigmatism, even in non-astigmatic subjects. In contrast to perceived isotropy, the correction of astigmatism does not shift the bias in VA from the natural axis of astigmatism. All these aspects suggest a need to analyze the coupling effects of SA and coma with defocus and astigmatism, while planning the treatments especially in patients with high offsets and HOAs. Understanding these coupling effects during treatment planning may help by correspondingly adjusting the target sphere and cylinder in refractive procedures to compensate for translational offsets. Furthermore, they can also help understand the potential impact of the pupil-measured SA and coma in manifest refraction. Several publications discuss these aspects in optics- and physics-oriented literature, however, a simple theoretical representation describing the refractive coupling effects of various aberrations with a pupil center to corneal vertex offset, and the clinical impact of treating these aberrations does not exist.

Lundström and Unsbo [20] presented a complete theory to transform Zernike coefficients analytically with regard to concentric scaling, translation of pupil center, and rotation. This matrix-based framework can be used to theoretically analyze the impact of applying a translational offset in various aberrations measurements, in addition to calculate the theoretical inter-relationship between various higher and lower order aberrations after offset implementation. Based on their methods, we present in this descriptive work, a simple and understandable account of the refractive coupling effects among various aberrations with an offset. This account can be a guide for the clinician to easily assess the potential impact of measured aberrations in eyes with a large pupil center to corneal vertex chord length (offset).

2. Materials and Methods

An algorithm was implemented in SCILAB (© Scilab Enterprises) based on the methods presented by Lunsdtrom and Unsbo [20]. The effect of translation was assessed only for SA and coma for a circular pupil of 6 mm without any rotation or scaling. Zernike coefficients up to the seventh Zernike order were given as an input to the simulation program. The Zernike coefficients after translation were obtained as an output. The output Zernike coefficients were recorded and analyzed with respect to the offset. Furthermore, interrelation between the input and output Zernike coefficients was analyzed. No patients were involved in the study as only simulated cases were analyzed.

2.1. *Effect of Spherical Aberration Translation*

The effect of SA translation was assessed with different simulation cases. All Zernike coefficient except C[4,0] (corresponding to SA) were set to zero. The value of C[4,0] was varied between 0 and +2 μm with a period of +0.4 μm. For each value of C[4,0], the input Zernike coefficients were translated for a distance of 0 to +1 mm with a period of +0.2 mm.

2.2. *Effect of Coma Translation*

The effect of coma translation was assessed with different simulation cases. All Zernike coefficient except C[3,1] (corresponding to horizontal coma) were set to zero. The value of C[3,1] was varied between 0 and +2 μm with a period of +0.4 μm. For each value of C[3,1], the input Zernike coefficients were translated for a distance of 0 to +1 mm with a period of +0.2 mm.

3. Results

The overall effect of SA and coma translation is summarized through the schematic presented in Figure 1. These interrelationships were validated in all the simulation cases. Their clinical implications are discussed in detail in the next section.

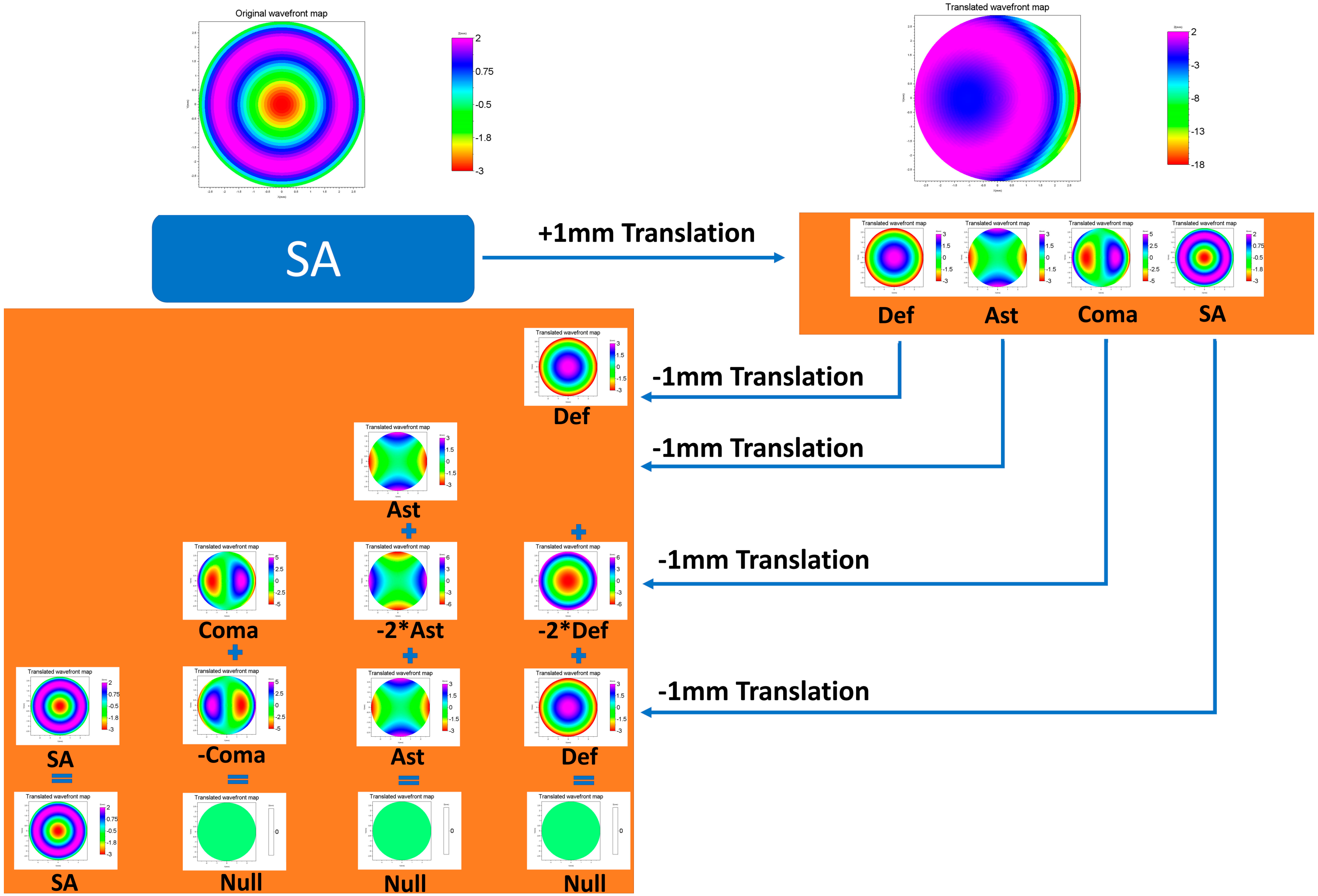

Figure 1. *Cont.*

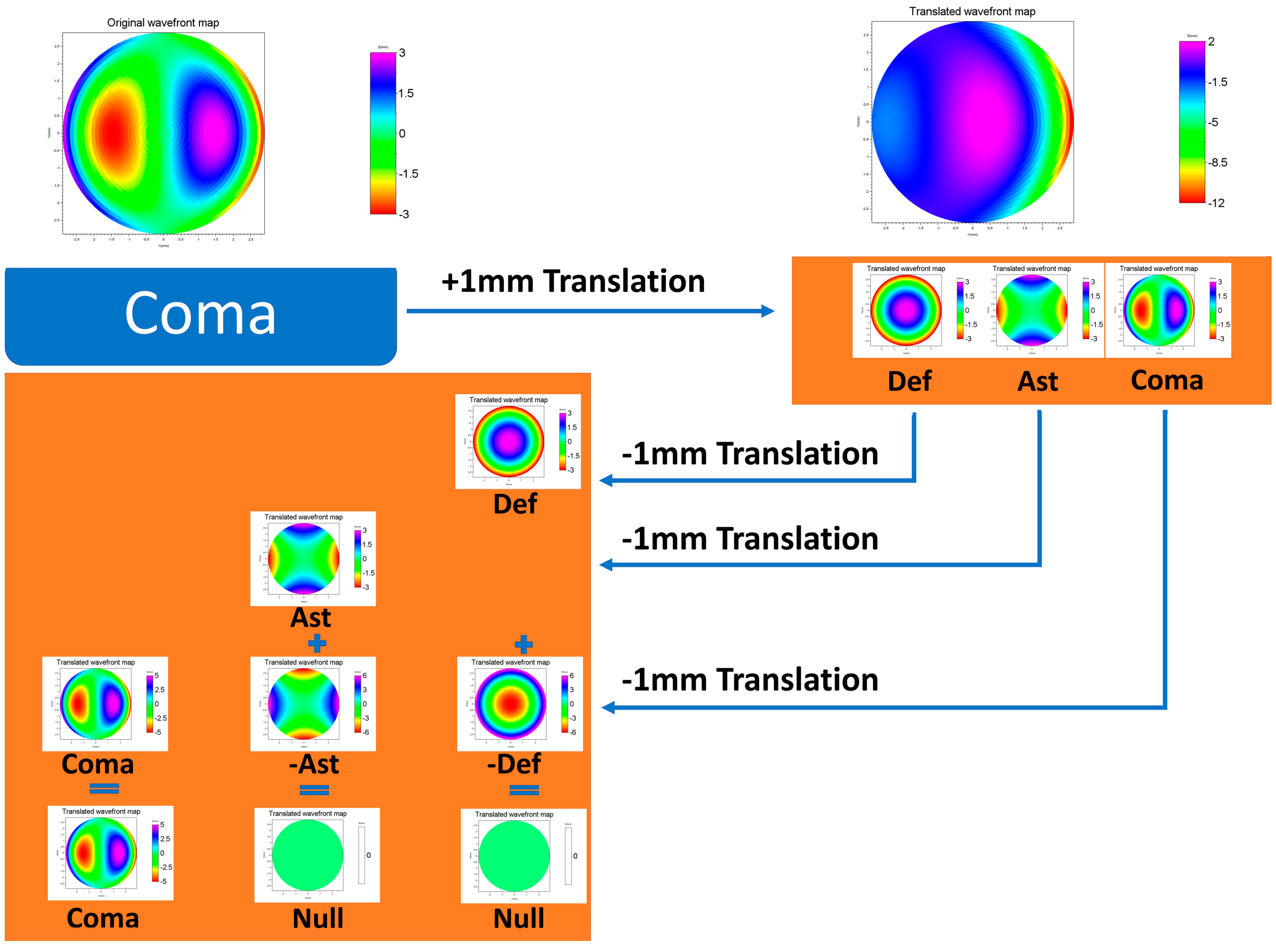

Figure 1. A schematic showing the effect of translation in spherical aberration (Top) and Coma (Bottom). Here, SA is spherical aberrations, Def is defocus, Ast is astigmatism and X represents the translation in horizontal axis with the positive and negative sign convention indicating the direction of translation. A +X translation in SA results in Def, Ast, coma and SA. A –X translation in Def results in the same amount of Def; in Ast results in same amount of Ast; in coma results in negative twice for Def, negative twice for Ast and the same amount of coma; in SA it results in Def, Ast, negative coma and the same amount of SA. Similar relationships can be interpreted for coma translation (bottom). Notice that a combination of all these aberrations resulting from –X translation results in the original higher order aberration (HOA), showing the theoretical equivalence between the effect of the same amount of translation in the positive and negative direction.

3.1. Effect of Spherical Aberration Translation

For the simulated test cases, the translation of SA (C[4,0]) in the positive direction on the horizontal axis resulted in horizontal tilt (C[1,1]), defocus (C[2,0]), cardinal astigmatism (C[2,2]), horizontal coma (C[3,1]) and the same number of SA (C[4,0]). The progression of cardinal astigmatism (C[2,2]), defocus (C[2,0]) and horizontal coma (C[3,1]) with respect to the offset is presented in Figure 2A–C, respectively. A comparison of the sign of the induced aberrations, due to translation of SA (C[4,0]) in other directions is summarized in the schematic shown in Figure 3.

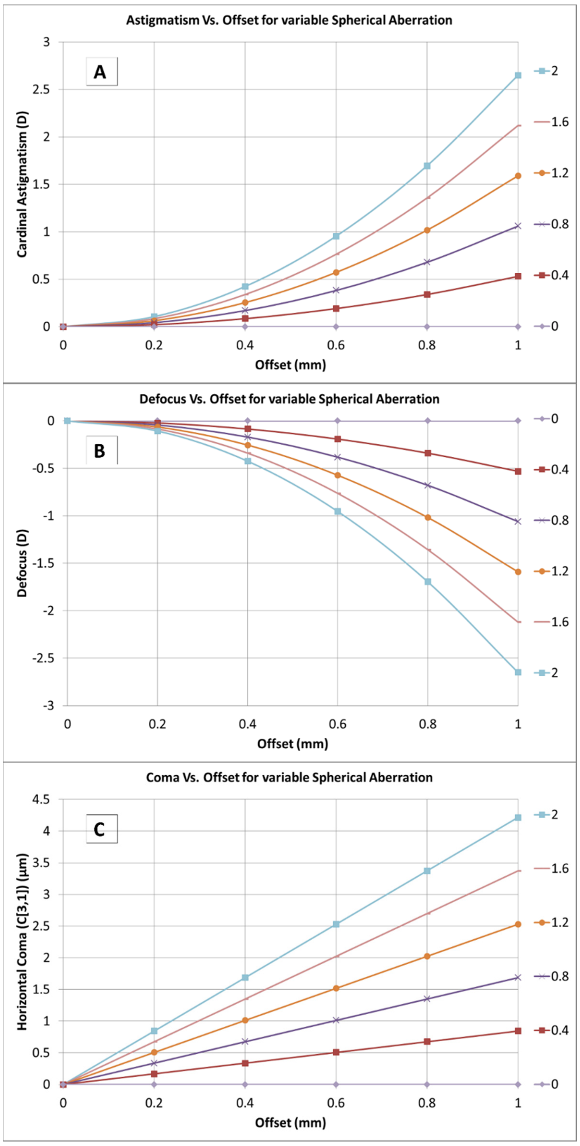

Figure 2. A progression of aberrations with respect to offset (0 to +1 mm) for a variable amount of spherical aberrations (SA) (0 to +2 µm). Here, offset represents translation; however, the results are presented with the terminology more popular in the field of refractive surgery. (**A**) Progression of cardinal astigmatism with respect to offset for variable SA. For an SA of +0.4 µm, a translation of 1 mm theoretically results in +0.53D of cardinal astigmatism. (**B**) Progression of defocus with respect to offset for variable SA. For an SA of +0.4 µm, a translation of +1mm theoretically results in −0.53D of defocus. (**C**) Progression of horizontal coma (C[3,1]) with respect to offset for variable SA. For an SA of +0.4 µm, a translation of +1 mm theoretically results in +0.84 µm of horizontal coma (C[3,1]).

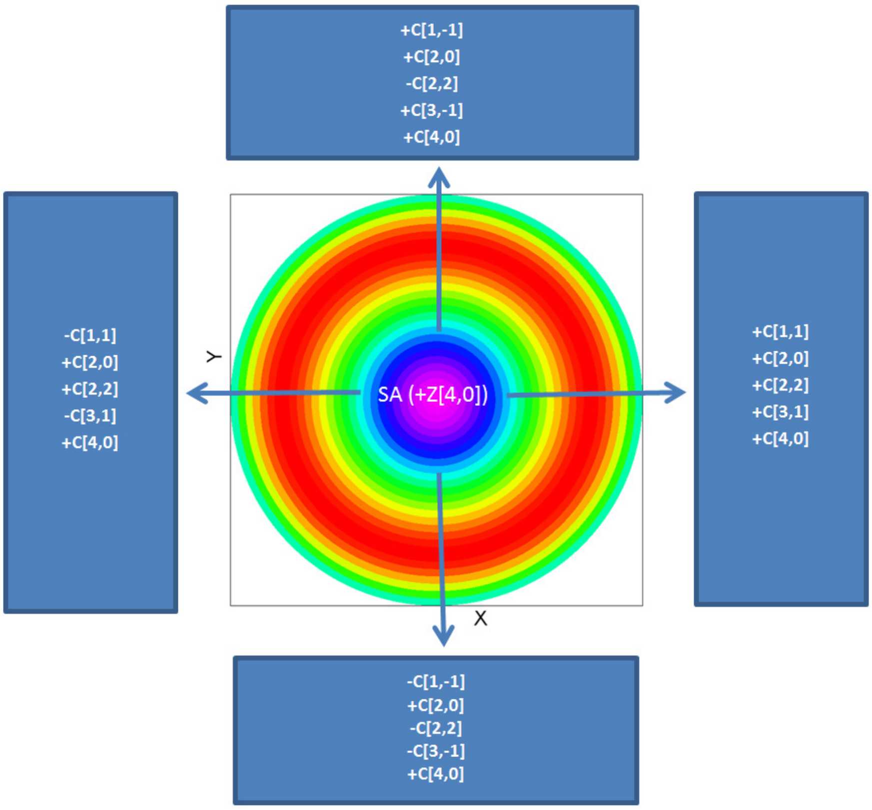

Figure 3. Effect of translation in spherical aberration (SA) (C[4,0]) in positive and negative direction in the orthogonal principal axes. Notice that translation in the horizontal axis results in induction of horizontal tilt (C[1,1]) and horizontal coma (C[3,1]), while translation in the vertical axis results in the induction of vertical tilt (C[1,−1]) and vertical coma (C[3,−1]). Astigmatism and SA remain unaffected from the axis of translation. In addition, in the horizontal axis, the direction of translation effects the sign of the induced horizontal tilt (C[1,1]) and horizontal coma (C[3,1]); while in the vertical axis, the direction of translation effects the sign of the induced vertical tilt (C[1,−1]) and vertical coma (C[3,−1]).

3.2. *Effect of Coma Translation*

For the simulated test cases, the translation in horizontal coma (C[3,1]) in the positive direction on the horizontal axis resulted in horizontal tilt (C[1,1]), defocus (C[2,0]), cardinal astigmatism (C[2,2]) and the same extent of horizontal coma (C[3,1]). The progression of cardinal astigmatism (C[2,2]) and defocus (C[2,0]) with respect to offset, for a variable horizontal coma (C[3,1]) is presented in Figure 4A,B, respectively. In order to put these results into perspective, the progression of cardinal astigmatism (C[2,2]) and defocus (C[2,0]) with respect to horizontal coma (C[3,1]) for variable offsets, is presented in Figure 5A,B, respectively. A comparison of the sign of the induced aberrations, due to translation of horizontal coma (C[3,1]) in other directions is summarized in the schematic shown in Figure 6.

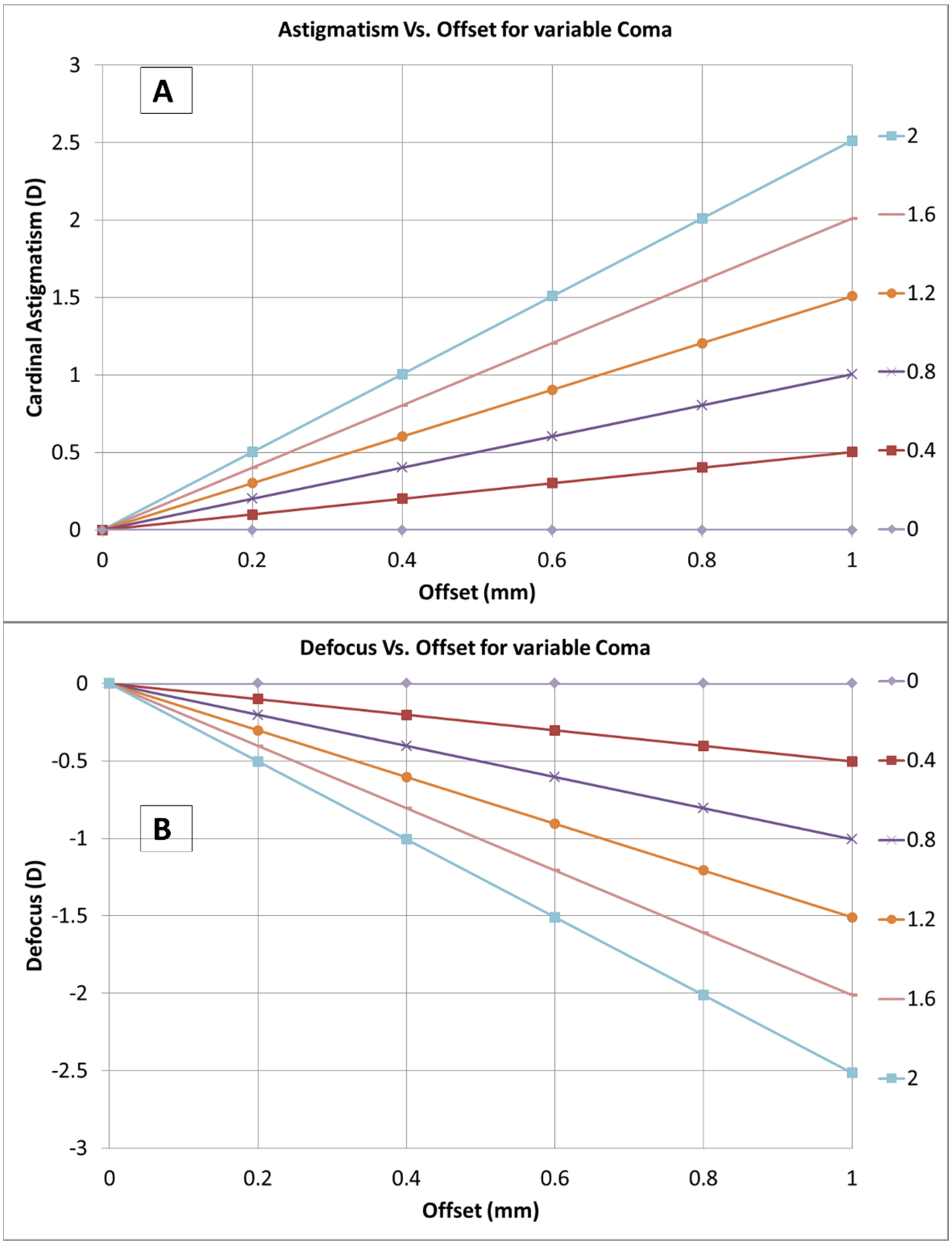

Figure 4. A progression of aberrations with respect to offset (0 to +1 mm) for a variable amount of horizontal coma (C[3,1]) (0 to +2 µm). Here, offset represents translation; however, the results are presented with the terminology more popular in the field of refractive surgery. (**A**) Progression of cardinal astigmatism with respect to offset for variable horizontal coma (C[3,1]). For a horizontal coma (C[3,1]) of +0.4 µm, a translation of +1 mm theoretically results in +0.5D of cardinal astigmatism. (**B**) Progression of defocus with respect to offset for variable horizontal coma (C[3,1]). For a horizontal coma (C[3,1]) of +0.4 µm, a translation of +1 mm theoretically results in −0.5D of defocus.

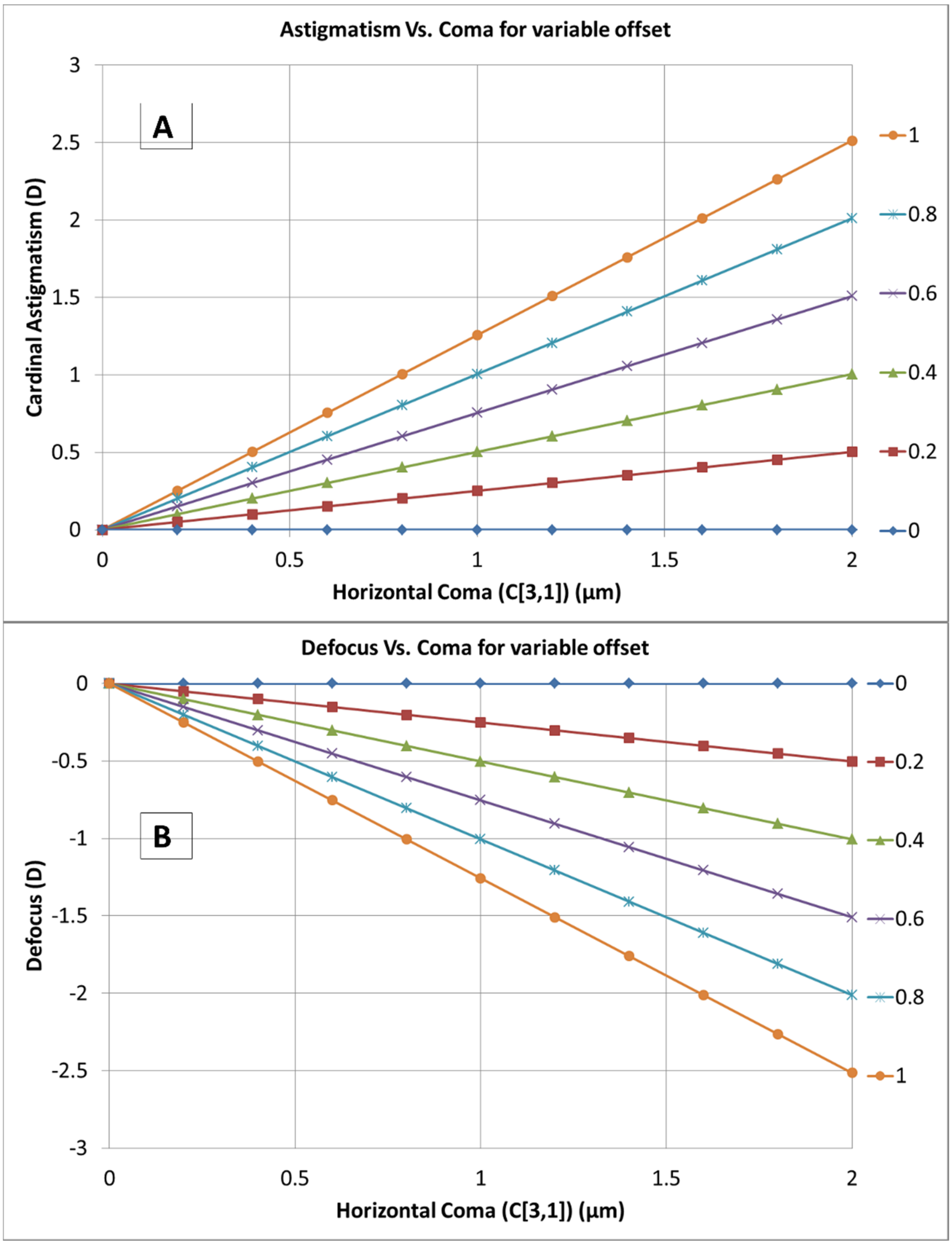

Figure 5. A progression of aberrations with respect to horizontal coma (C[3,1]) for a variable amount of offset (0 to +1 mm). Here, offset represents translation; however, the results are presented with the terminology more popular in the field of refractive surgery. (**A**) Cardinal astigmatism progresses linearly with respect to horizontal coma (C[3,1]) for a variable amount of offset. (**B**) defocus progresses linearly in the negative direction, with respect to horizontal coma (C[3,1]) for a variable amount of offset.

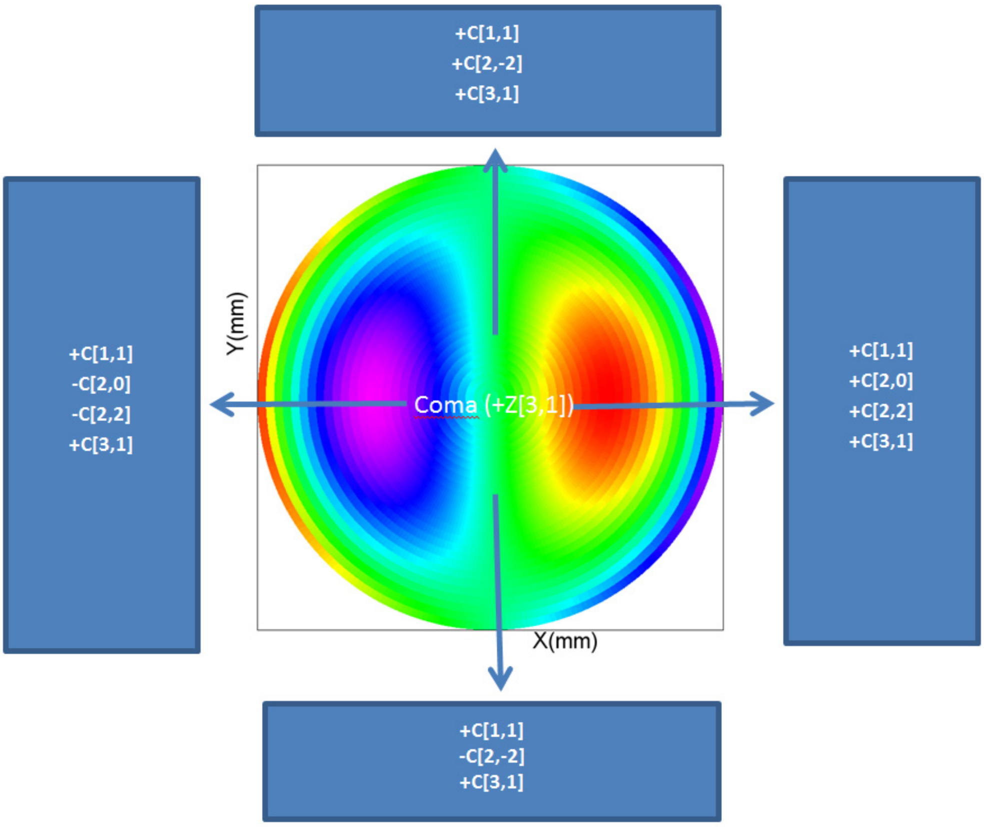

Figure 6. Effect of translation in horizontal coma (C[3,1]) in positive and negative direction in the orthogonal principal axes. Notice that translation in the horizontal axis results in induction of horizontal tilt (C[1,1]), defocus (C[2,0]), cardinal astigmatism (C[2,2]) and horizontal coma (C[3,1]); while translation in the vertical axis results in the induction of horizontal tilt (C[1,1]), oblique astigmatism (C[2,−2]) and vertical coma (C[3,−1]). In addition, in the horizontal axis, the direction of translation effects the sign of the induced defocus (C[2,0] and cardinal astigmatism (C[2,2]); while in the vertical axis, the direction of translation effects the sign of the induced oblique astigmatism (C[2,−2]) only.

4. Discussion

The results presented in this paper can help to understand the theoretical background of the interactions between aberrations and can aid the clinician assessing the theoretical impact in terms of HOAs and refractive couplings in patients presenting with a high offset (PC to CV chord length). As an example, if a patient presents with an extreme PC to CV chord length of 1mm in the horizontal axis and ocular aberrations, and in the event she/he is treated for aberrations with a PC reference, the theoretical impact of the translational offset during treatment (independent of the method of treatment) can be assessed with the presented results. For instance, treating this patient for SA of +0.4 µm (i.e., translation of 1 mm in 0.4 µm of SA) theoretically risks an induction of +0.53D of cardinal astigmatism, −0.53D of defocus and +0.84 µm of horizontal coma (Figures 1 and 2) in CV. Similarly, if the same patient presents with the same offset in the vertical axis, treating for 0.4 µm of SA theoretically risks an induction of −0.53D of cardinal astigmatism, −0.53D of defocus and +0.84 µm of vertical coma (Figures 1–3) in CV. Similar estimations can be made for treating horizontal coma (C[3,1]); treating this patient with an extreme offset of 1mm in the horizontal axis for a horizontal coma (C[3,1]) of +0.4 µm theoretically risks an induction of +0.5D of cardinal astigmatism and −0.5D of defocus (Figure 4) in CV. However, if the patient is treated with an extreme offset of −1 mm in the horizontal axis for horizontal coma (C[3,1]) of 0.4µm, she/he would be at risk of inducing −0.5D of cardinal astigmatism and +0.5D of defocus (Figures 4 and 6) in CV, theoretically.

Kamiya K et al. [21] retrospectively explored the explanatory variables relevant to the changes in coma-like aberrations in 91 eyes of 48 patients undergoing Laser-in-situ-Keratomileusis (LASIK). They reported that SE correction and the surgical technique are the most influencing factors in coma induction, however, no significant correlation with other clinical factors such as age, gender, astigmatism correction, mean keratometric readings, central corneal thickness, or eye tracking was found. In a cohort of 46 eyes, Padmanabhan P et al. [22] showed that the induced changes in tilt, oblique astigmatism, vertical coma, and SA were statistically significantly higher in eyes with decentered ablations than in eyes with well-centered ablations. The above findings lend more clinical evidence to the induction of coma and astigmatism from decentered SA brought about by a decentered spherical treatment. By the same token, translation also explains why hyperopic treatments are often plagued with induced astigmatism and coma, among others. Hyperopic eyes often have a large PC to CV chord, and failure to center the treatment fully onto the CV, leads to decentered ablation, and consequently decentered negative SA. Translation of SA leads to the induction of defocus, astigmatism and coma [23].

In addition to the aspect of centration, unintended translational offset can also be induced due to mechanical errors, irregular light conditions, dilation state of the pupil and unintended movements during the surgery. Measuring aberrations over a pharmacological dilated pupil and treating them over a non-dilated pupil typically results in a shift of the wavefront-guided ablation in the superotemporal direction and an induction of HOAs [24,25]. Furthermore, different light conditions between diagnostics platforms affect the pupil dilation state and can potentially induce a shift in HOA map during treatment. The main aberrations induced by decentration in refractive surgery are defocus, astigmatism, and coma [26]. Much larger offset values have been reported in Keratoconus patients [27]. A significant displacement of the Line of Sight [12] is observed in keratoconus and relates to the position of the cone on topography and the induced vertical coma measured by aberrometery [27]. In addition, eyes with keratoconus show approximately 5.5 times more HOAs than what is typical in normal eyes, with vertical coma and SA being the most dominant [28,29]. Due to the natural irregular shape of the cornea in keratoconic patients, higher offsets, and comparatively higher values of coma and SA than in the normal population [29], the impact of translational offset on the post-operative refraction is even more exaggerated. Symptomatic postoperative laser refractive surgery patients with irregular corneas have been reported to have HOA that are 2.3 to 3.5 times greater than asymptomatic postoperative LASIK and normal preoperative eyes, respectively [30].

The significance of ocular or corneal aberrations may be subject to misinterpretation whenever eyes with different pupil sizes or the application of different Zernike expansion orders are compared. To counter this problem, methods using simple mathematical interpolation techniques have been developed to rapidly determine the clinical significance of aberrations, without concern about pupil and expansion order [31]. Measuring and describing peripheral aberrations is also complicated by the fact that Zernike polynomials are defined for round pupils. A unit circle with orthogonal functions shapes the base of Zernike polynomials. In this study, we have presented the effect of translation in aberrations for circular pupils, however, similar methodology and theoretical modeling [15,32,33] can be utilized to calculate the theoretical impact on elliptical pupils. The ranges of offset tested in the simulations, both for SA and horizontal coma, cover the most extreme cases presenting in the clinics, however, the presented refractive couplings (shown in Figures 1, 3 and 6) hold true for values beyond the tested ranges. Furthermore, we restricted our analysis to the aberrations most commonly seen in patients with high offset values; however, this method can be extended to the entire Zernike pyramid. The results presented in this study are theoretical and can only give an estimate about the impact of translation for unique and major aberrations namely defocus, astigmatism, coma and SA. The impact of translation in any refractive procedures cannot be entirely explained by translation only in coma and SA. It must be observed that these aberrations are seldom seen in a unique manner, and must be linearly combined with other aberrations, under the influence of translation. We presented our results on coma and SA for simplicity and prevalence, but the model can be easily extended to generic HOAs; however, this may make the interpretation of each term more difficult in the clinical context.

Furthermore, using just SA and coma in our simulations, effectively (qualitatively) explained the clinical observations particular to the manifest refraction in decentered ablations.

This theoretical work applies clinically, especially in cases of corneal wavefront-guided and topography-guided laser ablations. In the former case, corneal higher order aberrations are already displayed for the treatment plan and the surgeons can use the results presented herein to evaluate the potential refractive and aberrational coupling effect of the treatment. However, in the case of topography-guided treatments, surgeons should be aware of the translational effect of PC centered aberrations by generating the Zernike decomposition of the topography based on the pupil center and evaluating the potential translational effect on the refraction. Nevertheless, the primary aim of this work was not to qualify a treatment type as suitable or not suitable for a particular patient, but rather to provide an easy means to quantify and reliably account for the magnitude of the effects to be expected, and potentially compensate for them. Still, considering these results, we could advocate, regarding the qualification of the treatment type, for not inducing approximately more than half the original aberration, that is, having a net positive effect and not replacing one aberration by inducing another. This would mean considering a 0.4μm SA (C[4,0]) and translating by +0.25 mm with a pupil diameter of 6 mm would theoretically result in induction of tilt (C[1,1]), −0.03D defocus (C[2,0]) or 11% of the original SA, +0.03D astigmatism (C[2,2]) or 8% of the original SA, and +0.21 μm coma (C[3,1]) or 53% of the original SA. Similarly, the translation of +0.4 μm of coma (C[3,1]) by +0.25 mm with a pupil diameter of 6 mm would theoretically result in induction of tilt (C[1,1]), −0.13D defocus (C[2,0]) or 41% of the original Coma, and +0.13D astigmatism (C[2,2]) or 29% of the original Coma. We would like to highlight that the examples provided here should not be misinterpreted. In this example, we presented that the effects of transversal deviations beyond 250 μm would likely produce noticeable and measurable effects in the refractive components. However, we do not mean that this is a sort of pass/fail criteria such that those transversal deviations would lead to uncertain outcomes. The implication of this work is rather the opposite, that we provide a means to account for those effects beforehand and are able to incorporate them (at least the low order, refractive effects) on the correcting profile (of whichever nature).

While there are several previous works dealing with this topic and providing some prior comparable findings [34–44], there are differential and novel aspects to our current work. Those works dealt with the effects of mispositioning of intraocular lensesIOLs on the visual performance, but do not provide a means for compensating those effects. The novelty of this present work does not reside in the fact that there are effects on HOAs associated with a change of the reference frame, which can be quantified. The difference lies mainly in the following three aspects.

The present work provides an easy explanation and allows a better interpretation of some clinical findings reported in the literature related to decentered corrections. For example, the fact that decentered corrections (of the adequate power) result in residual astigmatism; or the fact that in the presence of coma aberrations, a subjective astigmatism seems to provide a reasonable corrector. Further, the present work provides an easy explanation and allows a better interpretation of some clinical findings reported in the presence of non-coaxial visual systems (large deviations between the pupil center and the visual axis). For example, the fact that patients presenting natural coma may not suffer from the detrimental effect which would be expected for pupil-centered analyses; or the fact that the presence of regularly irregular HOAs (coma and trefoil) may not require wavefront-guided corrections. Finally, the present work not only provides an explanation and allows an interpretation of these clinical findings, but it actually provides a very simple quantification of the refractive measures (modifications of the correcting power to be planned) associated to account for these different clinical conditions (in particular after decentered corrections (be it IOLs or previous ablations or lenticule extractions; or for pathologies such as keratoconus or lenticonus))

In conclusion, for the procedures dependent on the wavefront measurement results, special attention must be paid while treating patients presenting with large offsets. Considering the analytical transformation of Zernike coefficients with regard to concentric scaling, translation of pupil center, and rotation, the refractive coupling effects among various aberrations with an offset can be theoretically estimated and must be respected as an indicator of clinical outcomes.

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