SUBJECTIVE REFRACTION: A NEW VECTORIAL METHOD FOR DETERMINING THE CYLINDER (3/3)

The refraction technique traditionally used to determine the corrective cylinder for a prescription has changed very little over the years, mainly due to the limitations imposed by subjective phoropters, which present lenses in increments usually no smaller than 0.25 D.
Today, thanks to phoropters with continuous power changes(*) that allow to simultaneously and accurately act on sphere, cylinder and axis, it is now possible to develop new refraction techniques. This series of three articles describes the principles of a new vectorial method for determining the corrective cylinder and presents the rationale for an associated automated cylinder search algorithm.

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KEYWORDS
Subjective refraction, vectorial refraction, dioptric space, cylinder search, cross cylinders, phoropter, refraction algorithm, Vision-R™ 800.

Following the last two articles (published by Points de Vue in November and December 2020), we now continue our overview and discussion of our new vectorial-based cylinder-determination method. In this third and final article, we compare the techniques used in "traditional" and "digital" refraction to find cylinder values and look at how each one is charted in the dioptric space. We then discuss the advantages and outlook offered by the new "Digital Infinite Refraction™" method.

4) The traditional refraction method for determining the cylinder: an indirect process with permanent system of reference changes that limit accuracy.

As previously explained, the traditional method for determining the cylinder consists of searching first for the cylinder axis, then the cylinder power and finally adjusting the sphere power. Each of these components must be tested a number of times.

To determine the cylinder axis, the practitioner searches for its direction in increments (for example 5°) between each axis direction tested until the final axis orientation is found, in the event of an equal blur perception in the two cross cylinder positions, or until the axis orientation in a 5° angle is established, in the event of an inversion in the patient's answers.

And to determine the cylinder power, practitioners search for its value by increasing (or reducing) it in increments of (-0.25) D until they find the exact value if there is an equal blur for both positions of the cross cylinder or to establish its value between two increments of (-0.25) D if there is an inversion in the patient's answers.

Let us again consider our example of a starting refraction formula of +1.00 (-2.00) 30°, represented by an initial vector located on the J0° / J45° plane (see Figure 7), and see how the refraction is found. The first steps

(*) Vision–R™ 800 phoropter with smooth power changes by Essilor Instruments involve looking for the cylinder axis, carrying out successive axis tests (turning over a cross cylinder whose handle is oriented according to the direction of the axis to be tested) and taking into account the patient's answers. For example, the practitioner tests the 30° direction (1), which the patient asks to have increased, then the 35° direction (2), which they also ask to have increased and, finally, the 40° direction (3), which they ask to have reduced. The practitioner then chooses an orientation between the last two directions tested, for example 38° (4), for which it proves, after another testing, that the patient no longer perceives any difference between the two positions of the cross cylinder. The axis found is therefore 38°.

Next, the practitioner searches for the cylinder power, carrying out several successive tests in which cylinder powers are increased (or decreased) in increments of (-0.25) D (turning over a cross cylinder whose main meridians correspond to the cylinder axis to be tested) and taking into account the patient's answers. For example, the practitioner thus tests the powers that the patient successively asks to have increased – (-200) D (4), then (-2.25) D (5) and finally (-2,50) D (6) and then the power (-2.75) D (7) that he asks to have reduced. The practitioner reduces the cylinder power (-0.25) D and since (-0.50) D has been added to the initial corrective cylinder, they adjust the sphere +0.25 D, reaching the final formula of + 1.25 (-2.50) 38°.

Graphically speaking, this cylinder search translates in the dioptric space to the fact that:

- The first steps – (1), (2), (3) and (4) – in the cylinder axis search take place in the J0° / J45° plane along a "circular" line of constant cylinder power of (-2.00) D, leading to an axis location between 35° and 40° and found, in this example, at 38°.
- The following steps – (4), (5), (6) and (7) – in the cylinder power search take place along a constant axis direction (38°) as the power is increased, which is to say radially moving away from the system of reference's origin. With this increase in cylinder power, the spherical equivalent power (or average power) decreases, which translates graphically to the fact that points (5), (6) and (7) progressively "sink" below the J0° / J45° plane as the cylinder power increases.
- The last step (8) in the cylinder reduction and final sphere adjustment involves a radial reduction in cylinder power and an adjustment toward the convex of the sphere power and therefore by a raising of point (8) on the J0° / J45° plane (a +0.25 D compensation of the sphere after an increase of (-0.50) in the cylinder).

At this point, we can make the following observations:

- The process used in the traditional technique for cylinder search appears to be quite indirect. This can be clearly seen, in Figure 7, by the way in which the dioptric space is explored: first in a "circular" way for the axis search, and then "radially" for the power search, with an effect on the "altitude" which is then compensated for. Remember that this exploration method is directly linked to the limitations imposed by traditional phoropters and, more particularly, the fact that action on the sphere, cylinder axis and cylinder power can only ever be performed separately and in increments of 0.25 D.
- The cylinder search using the traditional technique takes place in a system of reference that is modified with each of the patient's answers: during a cylinder axis change because the cylinder power has not been adjusted after a modification to the axis and also during

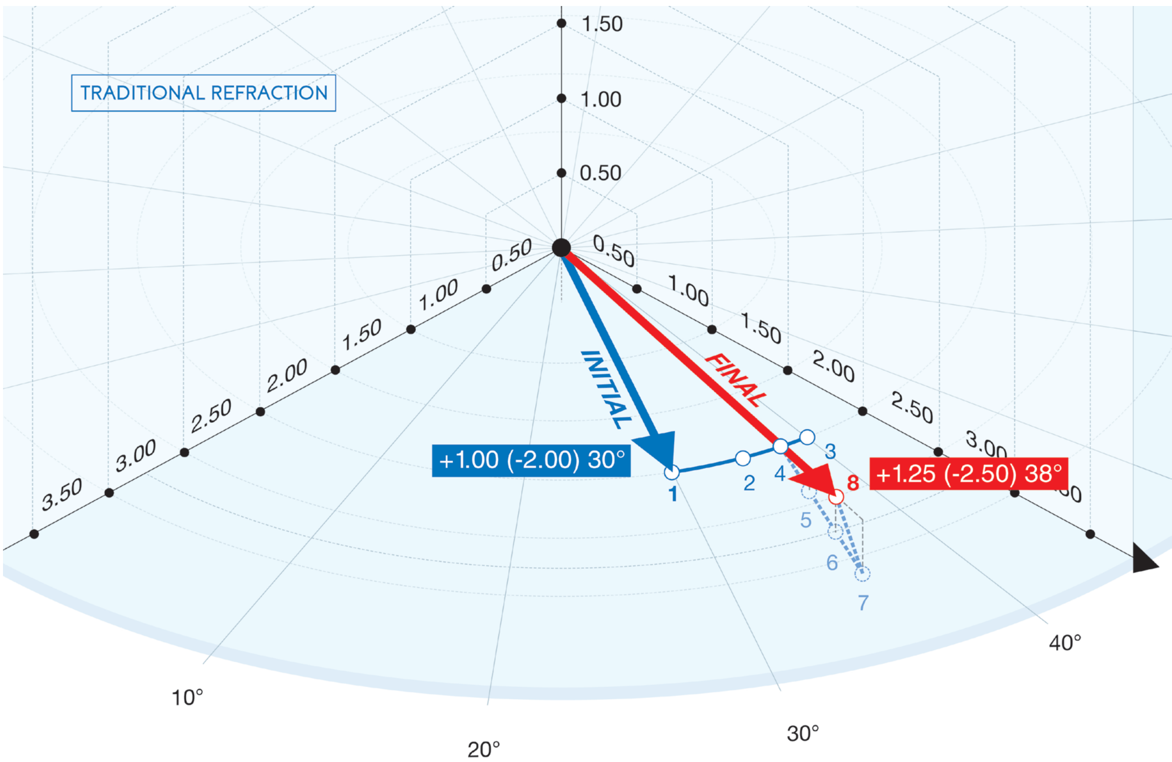

Figure 7: Determining the cylinder using the "Traditional Refraction" method:
Cylinder axis then cylinder power, followed by a sphere adjustment.

a cylinder power change because the sphere power has not been adjusted to keep the spherical equivalent power constant. The practitioner must determine the cylinder axis and power separately, although they are intimately linked in their polar expression and any modification to one of them inevitably has an influence on the patient's perception of the other. Thus, during the cylinder axis search, each axis test performed – as we have seen in Part 3a of this publication – perpendicularly to its direction is made in an orientation that changes with each modification to the cylinder axis. During the power search, each test is carried out with a variable spherical equivalent power. As a result, the cylinder search system of reference "moves" over the course of the cylinder search and makes its determination less accurate. It should also be noted that there is variability and potential inconsistency in the patient's answers.

– During the cylinder search, the power and axis variation increments most often remain constant: a 0.25 D increment for the power, as imposed by the lenses available in traditional phoropters, and a 5° increment for the axis, as is offered by default by the phoropter or chosen by the practitioner even when other options are possible. It should be noted that these increments are generally the same regardless of the refraction value, whether it is high or low, and regardless of the patient's sensitivity to dioptric changes. Let us also note that these increments are often greater than the patients' dioptric sensitivity. In one study, it was found to be under 0.25 D for 95% of the patients and under 0.125 D for 44% of them, or nearly one of every two patients.[7]

– In the Jackson cross-cylinder method, we compare the blurred and variously distorted vision of points (or optotypes) that are not always easy for the patient to evaluate and may consequently require repeated tests. The cross-cylinder value of +/- 0.25 D generally used can prove insufficient in generating differences that are significant enough to be perceived by the patient. The search for the cylinder axis, like that for the cylinder power, ends when an equally blurry vision is found for both positions of the cross cylinder, which can be difficult for the patient to evaluate and can prove troubling to them. It may indeed seem strange to them that the cylinder search stops when their vision is still blurry in all directions.

– In the traditional cylinder search process, the practitioner's experience is essential. This is because mastery of the Jackson cross-cylinder technique requires a lot of practice. The practitioner must evaluate and interpret each of the patient's answers to perform the cylinder search and make decisions, for example to modify the cylinder axis direction in the direction requested by the patient, and to stop the cylinder axis search to begin the power search, or to consider that the cylinder search is finished. Furthermore, the practitioner has to simultaneously perform a refraction and draw up a prescription, which is to say interpreting the results to decide upon the prescription: for example, under-correction of the cylinder power or sphere, or a moderation in the change of axis or the decision to stop searching for the cylinder. For these reasons, a refraction result can depend on the practitioner who performs it, which means there is inevitably a certain amount of variability. Traditional subjective refraction can therefore be viewed as doubly subjective, since it depends on both the patient's evaluation and the practitioner's interpretation!

It is clear that the traditional refraction method for determining the cylinder has intrinsic limitations, both in terms of consistency in the patient's answers and accuracy of the dioptric increments used. It cannot be used to determine the refraction with enough accuracy to match patients' true dioptric sensitivity.

2) Determining the cylinder with Digital Infinite Refraction™: a direct process with a consistent system of reference and two iterations to ensure great precision.

The digital refraction method for finding the cylinder involves – according to the choice that has been made – searching first for the cylinder power component according to the initial refraction axis direction and then the cylinder axis component along a direction perpendicular to this initial axis. This is made possible by vector management of the cylinder components, which induces an adjustment to the cylinder power with each modification to its axis. The cylinder search is also performed with a constant spherical equivalent power throughout the entire process. This search is based on two new principles:

– First, the cylinder power component is always tested in the direction of the axis of the initial refraction – or in a parallel direction in the dioptric space – and the cylinder axis component is always tested in a direction perpendicular to the direction of the initial axis. The search for the power and axis components is performed in two fixed directions and independently of each other.
– Second, an inversion in the patient's answers is always be sought – rather than equal answers as in the traditional method – and a statistical estimate of the most probable value of each power and axis component is made for all of the answers given by the patient, rather than (in the traditional method) the practitioner making a decision, for axis and then power, according to their evaluation of the patient's last answer.

The search for the power component begins according to the initial axis with an increase – or reduction – in power by one increment, chosen but configurable, of (-0.35) D until an initial inversion in the patient's answers is obtained. During this phase, the axis remains fixed and only the cylinder power varies with a corresponding adjustment to the sphere value. An initial power value is obtained in this way, midway between the last two cylinder powers tested.

The search for the axis component then continues in a direction perpendicular to the initial axis direction, testing the axis variation effects induced by a 0.70 D variation on either side (using a virtual cross cylinder of +/- 0.35 D whose value was chosen but can be modified in the algorithm). With each of the patient's answers, the axis is modified as requested and in a direction that remains constant in the dioptric space with an adjustment to the cylinder power and the corresponding compensation to the sphere power. The second inversion in the patient's answers is then sought, relative to the axis direction this time. In this way, an initial axis value is determined midway between the last two directions tested – the ones giving rise to contradictory answers from the patient.

Let us take another look at our example of an in initial correction of +1.00 (-2.00) 30°, represented by an initial vector located on the J0° / J45° plane (Figure 8). The first steps involve carrying out several power tests (using the digital refraction technique described previously) in the 30° direction and according to the patient's answers. For example, the practitioner tests the powers that the patient asks to have increased: (-2.00) D (1) and then (-2.35) D (2), and finally the power he asks to have reduced (-2.70) D and thereby obtain an initial cylinder power estimate of (-2.52) D according to the 30° axis, which is the value midway between the last two powers tested. It should be noted that each power modification is always accompanied by a compensation in the sphere, of an opposite half-value, to keep the spherical equivalent power constant.

Next, the cylinder axis component search is performed in the direction perpendicular to the initial axis (using the digital refraction technique) and according to the patient's answers. The practitioner first tests the 30° axis (4), which the patient asks to have increased, then the 34° (5) axis, which he also asks to have increased, and finally the 38° axis (6), which he asks to have reduced. The inversion in answers sought is thus obtained and the final angle value is the one between the last two directions tested, or 36°. Note that for each axis variation, the cylinder power is adjusted and the sphere power is compensated as a result.

In this way, we reach the formula +1.24 (-2.49) 36°, after an inversion in answers according to the initial axis correction and an inversion in answers according to the perpendicular direction.

Graphically speaking, this translates in the dioptric space to the fact that:

– The first steps – (1), (2), (3) and (4) – in the cylinder power component search are made in the 30° direction and remain located on the J0° / J45° plane, unlike what happens in traditional refraction, in which they progressively shift along the J0° / J45° plane.
– The following steps – (4), (5), (6) and (7) – in the cylinder axis component search take place in a direction perpendicular to the direction of the initial axis, starting from point (4). These points are aligned according to the same straight line, which mediates the segment linking points (2) and (3) – which is to say the perpendicular line in its middle – rather than along a circle centered on the origin of the system of reference corresponding to the initial cylinder power as in traditional refraction. These points are all rigorously located on the J0° / J45° plane, in which the entire cylinder search is performed.

Several observations can be made here:

– The digital method for determining the cylinder is much more direct than the traditional one. Its representation in the dioptric space (Figure 8) shows that the search begins radially, according to the initial cylinder axis, to find the cylinder power component, and then along a line perpendicular to the direction of the initial axis to look for the cylinder axis component, always remaining on the J0° / J45° plane. This is due to the fact that, as explained previously, any variation in the cylinder power is automatically compensated for in the sphere power and, thanks to the management of vectorial components, any modification to the axis brings about an adjustment in the cylinder power and therefore a compensation in sphere power.

– The system of reference in which the cylinder search is performed remains constant throughout the search: the power and axis tests are always done in the same respective perpendicular directions: the initial cylinder axis direction for the power search and its perpendicular direction for the axis search. In other words, the cylinder search is performed according to its vectorial components in constant directions. This vectorial technique allows the practitioner to maintain greater consistency in the patient's answers and to increase precision in determining the cylinder. It offers the possibility of cumulating the patient's answers according to two constant directions and estimating the cylinder power and axis statistically, rather than basing them on the patient's final single answer as is the case in traditional refraction. We will look at this again later.

– The cylinder search becomes more accurate during the refraction process:
  - The cylinder power modification increment is initially higher in the digital method than in the traditional one – (0.35) D rather than (0.25) D – and this allows for a more rapid power search and facilitates the patient's answers. This increment is then progressively reduced. It is halved after the first inversion in the patient's answers and then fine-tuned further. It may also be increased again if the patient's answers are inconsistent. Note that in traditional refraction, this increment would remain constant at 0.25 D throughout the entire process.
  - The cylinder axis modification increment is dioptrically constant and identical to the one used to search for the cylinder power: 0.35 D to start with. The advantage of this is that it creates axis changes which, translated to diopters, generate variations in uniform perceptions for the patient compared to those perceived in the power search. This increment is then reduced by half upon the first inversion in the patient's answers – relative to the axis test – and will then be fine-tuned further. It may also be increased again if the patient's answers are inconsistent.

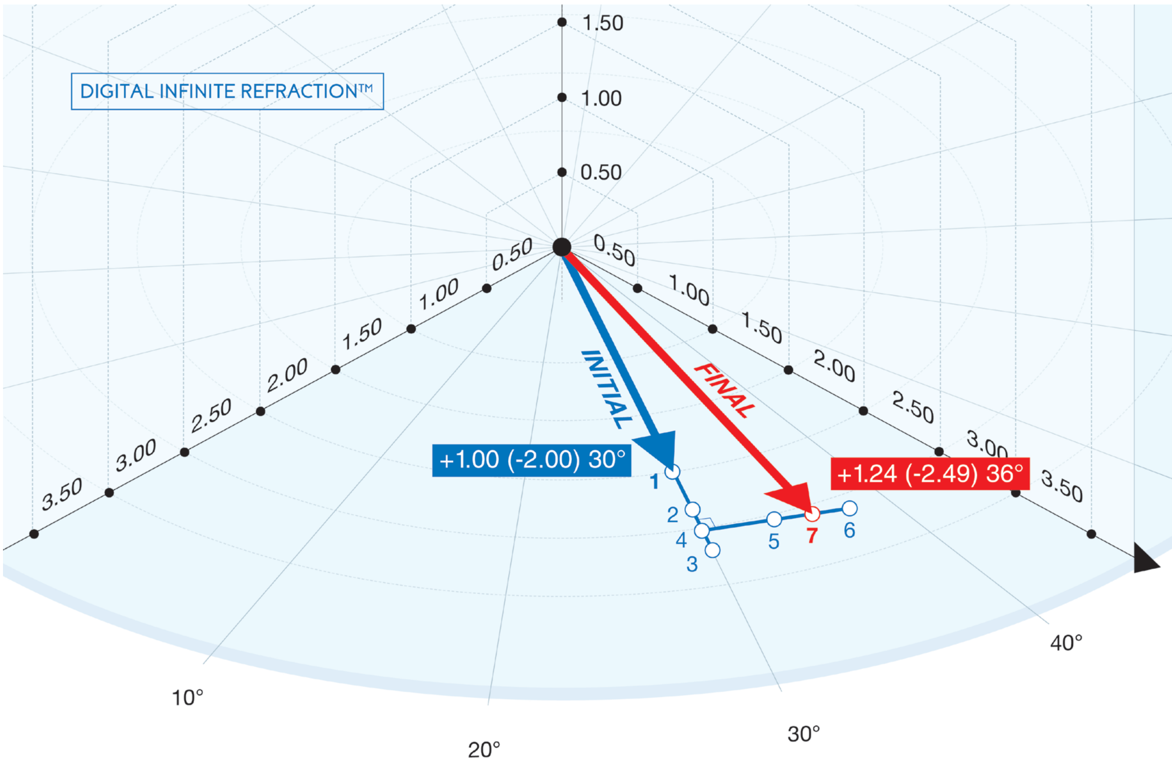

Figure 8: Determining the cylinder using the "Digital Infinite Refraction™" method:
cylinder power then cylinder axis, with simultaneous compensation of cylinder power
and a constant spherical equivalent power

Inversely, in traditional refraction, the axis variation increment is chosen by the practitioner and is often 5° regardless of the cylinder value. This has two noteworthy consequences: first, the dioptric effect produced by the axis cylinder change can vary from one patient to another since it depends on the cylinder power and second, this effect is not uniform with the one used to search for the power. This applies to all patients. In other words, the fact that the axis modification increment is chosen by the practitioner and can be constant angularly makes it very dioptrically variable!

– In digital refraction, the cylinder power and axis components are evaluated by establishing the value sought and on the basis of inversions in the patient's answers. They are estimated independently of each other and in a statistical way over all of the patient's answers. We will look at this again later.

  In traditional refraction, the cylinder power and axis values are, to the contrary, established according to the patient's final answer – once they indicate that two positions have the same blurriness – and a decision made by the practitioner. It is therefore inevitable that the process involves a certain amount of subjectivity, which means variability.

With the Digital Infinite Refraction™ method, which uses an automated algorithm, the cylinder search is conducted independently of the practitioner's techniques and decisions. It involves determining the patient's refraction value, which the practitioner will then interpret and modify to draw up the prescription.

A second cylinder search iteration for greater precision

In the Digital Infinite Refraction™ approach, the cylinder search does not consist of a single determination of the cylinder as it does in the traditional technique. Rather, the search algorithm* offers a second verification of the cylinder power and axis after the first search. The idea is to fine-tune the refraction found in the first iteration by searching (in the same directions in the dioptric space) for two new inversions in the patient's answers. When this is done, all the answers are accumulated according to the two fixed directions – the cylinder power and axis components – to carry out a statistical analysis to evaluate the cylinder power and axis thresholds while simultaneously verifying the consistency of the patient's answers. Let us take a closer look at this second iteration.

After the first cylinder search, the following takes place:

– First, a second verification of the cylinder power component is performed, again in the direction of the initial 30° axis from our example, until a new inversion is observed in the patient's answers. This second evaluation complements, fine-tunes and confirms the first cylinder power evaluation already performed in this direction during the first iteration.

– In the same way, a second verification of the cylinder axis component is carried out, again perpendicularly to the initial axis direction, until there is a new inversion in the patient's answers. This is how a more precise evaluation of the axis can be performed.

– During each of these answer inversions, the dioptric increment of variation in power or axis is again reduced in order to fine-tune the search. Note that this increment is nevertheless kept at a level sufficient to be perceived by the patient but that it can be increased again if inconsistencies are observed in the patient's answers.

- For both cylinder components – power and axis – all of the patient's answers are taken into consideration and analysed statistically. More specifically, the answers are accumulated in the initial cylinder axis direction for the cylinder power component and in the direction that is perpendicular to it for the cylinder axis component. According to each of the directions that are determined, for all the answers the patient gives during the first and second iterations, the most probable value is estimated for the cylinder power and axis components. This is how the algorithm determines the thresholds for the cylinder power and axis, which represent an accurate refraction result. They are calculated using Cartesian coordinates and plotted with polar coordinates.

- The consistency of the patient's answers is verified throughout the search process, and this is what determines at which point the process should end. As a result, the more consistent the patient's answers are, the less time the cylinder search process takes. Inversely, if the patient's answers are inconsistent, it can take a while to achieve the reliability needed.

In this way, the practitioner reaches a final refraction of +1.21 (- 2.42) 35°.

Graphically speaking, this second iteration of the cylinder search translates in the dioptric space (see Figure 9) to the fact that:

- After steps (1) through (6) of the first iteration, which lead to the first refraction estimate, the examination continues with steps (7) through (12), in which the refraction is fine-tuned.

- The second verification of the cylinder power component – steps (7), (8) and (9) – takes place along a line parallel to the initial cylinder axis direction in the dioptric space: in Figure 9 we can see that the straight line joining points (7), (8) and (9) is parallel to the one joining points (1), (2) and (3). The initial direction used to search for the cylinder power component is kept constant while the axis component is adjusted to its most probable value after the first iteration.

- The second verification of the cylinder axis component – steps (10), (11) and (12) – is performed along a direction perpendicular to the cylinder's initial axis. In Figure 9 we can see that it is parallel to the right line joining points (4), (5) and (6). The initial direction used to search for the cylinder axis component is kept constant while the power component is adjusted to its most probable value after the second iteration.

- Another noteworthy detail is that unlike what happened during the first cylinder search iteration, point (7) is not found exactly midway between points (5) and (6), the points for which the inversion of the patient's answers arose, but is slightly offset. Similarly, we can see that point (10) is not midway between (8) and (9) but also a bit offset with respect to them. This comes from the fact that starting from the second cylinder search iteration, these points result from an estimate of the new "point" to be tested based on the patient's answers for the power and axis components, respectively. In other words, the answers already given by the patient during the first iteration are taken into consideration in the second iteration. The main advantage of the vectorial refraction technique is that one can examine the power and axis components independently of each other and accumulate answers according to these two directions to analyse them statistically and separately evaluate the most probable cylinder power and axis values.

Discussion:

Let us now discuss the advantages that Digital Infinite Refraction™ offers and the outlook for future developments that it makes possible:

- Consistency and accuracy: the vectorial approach used to search for the cylinder allows practitioners to carry out refraction with a consistent system of reference: on the one hand, the same dioptric system of reference is used throughout the search process and on the other, the dioptric effects produced during the searches for power and axis remain consistent. This technique allows to very accurately determine the cylinder, in 0.01 D and 1° increments, which was never possible until now.

- Psychometric methods: the new method allows us to implement threshold search techniques like the ones traditionally used in psychophysics. We are thus no longer limited to evaluating sphere, cylinder power and cylinder axis values as we are in traditional refraction, but rather look for the most probable threshold values for the three Cartesian components of refraction: spherical equivalent, the J0° horizontal cylinder component and the J45° oblique cylinder component, determining them statistically. The refraction thus becomes a truly physiological measurement!

- Precision in line with patients' true dioptric sensitivity: while traditional refraction using lenses in 0.25 D increments is not precise enough to match patients' real dioptric sensitivity (often less than 0.10 D), the new technique using 0.01 D optical increments makes it possible to determine refraction with a high degree of accuracy, the only limitation being the patients' dioptric sensitivity. It is no longer the phoropter that limits accuracy in refraction but the patient's sensitivity. Even better, the new technique also allows to evaluate the dioptric sensitivity of each patient during the refraction examination itself, thus offering a new complementary parameter to accompany the refraction result and help interpret it.

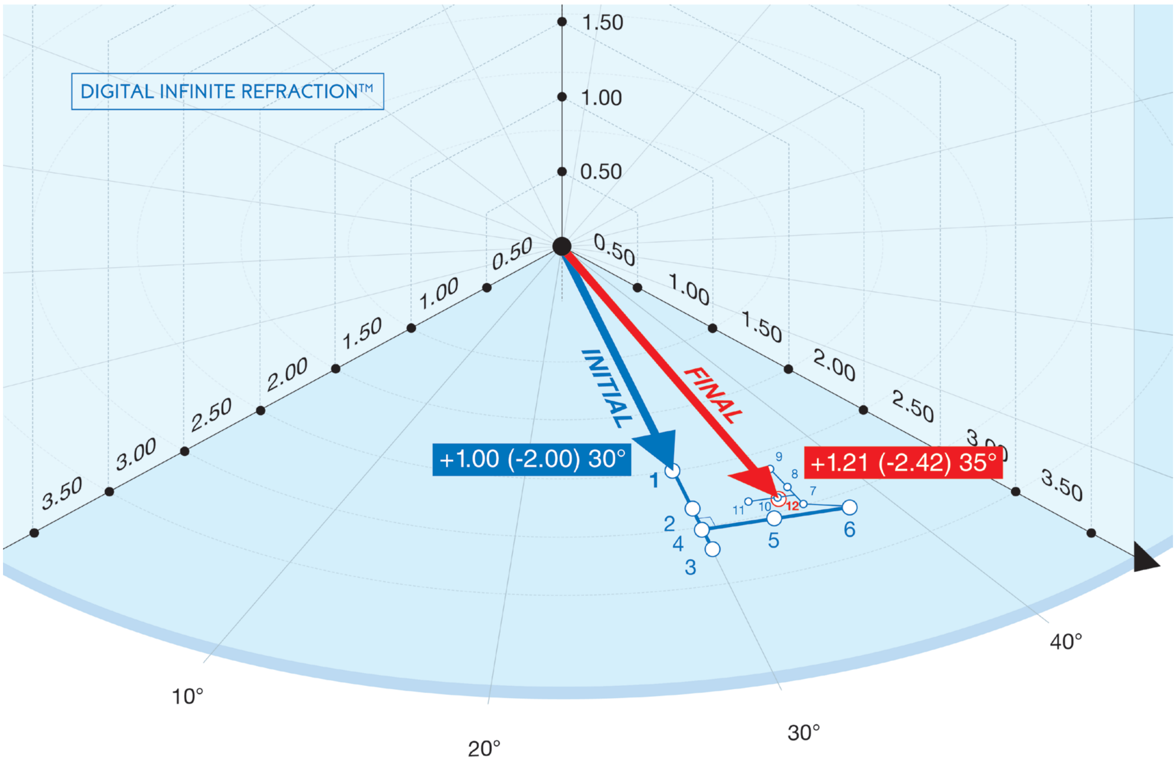

Figure 9: Determining the cylinder using the "Digital Infinite Refraction™" method

A double iteration of cylinder power and axis search in a single sequence

– Refraction-assistance algorithms: the formalisation of refraction techniques, in particular the one for the cylinder search, in automated refraction tests and programs allows practitioners to offer a certain standardisation in refraction examination methods. It should help eliminate the inevitable variability in practices and increase the reproducibility of refraction results from one practitioner to another, thereby making subjective refraction more objective!

– A new "refraction then prescription" sequence: the new approach also allows for a refraction sequence that differs from the traditional approach. Initially, this involves determining a subjective refraction value using the phoropter's algorithms and then in a second step, interpreting this result to draw up a prescription. Thus, unlike in the traditional simultaneous refraction-prescription process, which is to say interpreting the results during the refraction examination itself, with the subjectivity inherent in it, a new "refraction then prescription" sequence becomes possible. This new approach can help dissociate "refraction" from "prescription" and thus transform the way is refraction is viewed and performed.

– Corrective lenses in 0.01 D increments: although refraction can now be determined in 0.01 D increments, this accuracy clearly has no advantage unless corresponding optical corrections can also be offered. Happily, lenses are now available in 0.01 D increments thanks to the digital surfacing technology developed more than 10 years ago. Today, the greater accuracy now possible with the new phoropters allows us to offer patients high-precision corrections.

Conclusion:

Although subjective refraction methods have remained virtually unchanged for over a century, they are now undergoing a major change. The advent of phoropters offering continuous power changes has made new subjective refraction techniques possible and allowed us to rethink our approach to subjective refraction. As we have described in this series of three articles, the corrective cylinder search can be performed using a new vectorial technique that is both more consistent and more accurate. Similar approaches have also been developed for other refraction tests: a new technique for fogging and unfogging, an automated sphere determination, an exact binocular balance determination, an approach to and automated measurement of near-vision addition, etc. The rationale developed for each of these tests translates to algorithms implemented in the automated refraction tests. The succession of these various tests makes it possible to create refraction programs that the practitioner can use as is or personalise according to need.

Refraction tests and programs using the next generation of phoropters(*) are now available. With the total flexibility of the optical module and its controls, great scope for new refraction-related research and innovation is now opening up. In the future, even more innovative new tests, algorithms, programs, protocols and methods will emerge. And since these next-generation phoropters are connected tools, it will be possible to remotely update their software to integrate the latest advancements on a regular basis. Since the programs are also so easy to use and the phoropters are connected, the techniques can also transform the very way refraction is performed: delegated refraction, remote refraction and even self-refraction may become possible. We are clearly at the beginning of a revolution in refraction possibilities!

The technology of the new phoropters will make it possible to automate and standardise refraction techniques and determine patients' correction with greater accuracy. It will also make practitioners' day-to-day work easier, since they need simply monitor the automated processes, intervening as necessary. They must therefore thoroughly understand the workings of the algorithms involved in the refraction process. It is our hope that this publication has increased their understanding of the admittedly rather complex algorithm for vectorial-based corrective cylinder searches. But above all, we hope that it will promote the adoption and usage of automated cylinder determination processes by eye-care-professionals so that they can offer patients (even) more accurate optical correction of their astigmatism.

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KEY INFORMATION:

- In the traditional refraction method, the cylinder is determined in an indirect process with continually changing system of reference, which limits precision.
- In the digital refraction method, the cylinder is determined using a direct process with a consistent system of reference and double iteration to ensure a high level of precision.
- The new Digital Infinite Refraction™ method offers greater refraction accuracy thanks to its use of evolving automated algorithms that open up new possibilities in terms of making refraction exams easier.